NASA/CR-2015-218969

Description, Usage, and Validation of the MVL-15 Modified Vortex Lattice Analysis Capability

Thomas A. Ozoroski
Analytical Mechanics Associates, Inc., Hampton, Virginia

November 2015

NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

Access the NASA STI program home page at http://www.sti.nasa.gov

E-mail your question to help@sti.nasa.gov

Fax your question to the NASA STI Information Desk at 443-757-5803

Phone the NASA STI Information Desk at 443-757-5802

Write to:
STI Information Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320

NASA/CR-2015-218969

Description, Usage, and Validation of the MVL-15 Modified Vortex Lattice Analysis Capability

Thomas A. Ozoroski
Analytical Mechanics Associates, Inc., Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 2015

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Contents

List of Tables v
List of Figures vii
1.0 Introduction 1
2.0 Symbols 2
Greek Symbols 3
Abbreviations 3
3.0 Modified Vortex Lattice 5
3.1 Background Theory 5
3.2 Scope 7
3.3 Required Files 7
3.4 Setup and Analysis Files 7
4.0 Input File Examples, Definitions, and Formats 8
4.1 Input File: *in_2d_geom.txt* 8
4.2 Input File: *in 2d geom variation template.txt* 8
4.3 Input File: *in_2d_aero.txt* 12
4.4 Input File: *in_alphas.txt* 16
4.5 Input File: *in_analysis.txt* 18
4.6 Input File: *in_wing1x.txt* 20
4.7 Input Files: *in_wing(2x-5x).txt* 20
5.0 Output File Examples, Definitions, and Formats 26
5.1 Output File: *out_aero.txt* 26
5.2 Output File: *out_span.txt* 30
5.3 Output File: *out_geom.txt* 33
5.4 Output File: *out_xzang.txt* 36
5.5 Output File: *out_diag.txt* 36
6.0 Geometry and Aerodynamics Setup Files 39
6.1 Wing Geometry Setup Utility 39
6.1.1 Wing Panel Geometry Calculations 39
6.1.2 Flap Geometry Definitions 39
6.2 MVL-15 2d-Variants Utility 44
6.2.1 Airfoil Geometry Generator 44
6.2.2 Airfoil Aerodynamics Modifications 44

7.0 Analysis and Results Presentation 46
7.1 MVL-15 3d-Results Presentation Utility 46
7.1.1 Geometry Charts 46
7.1.2 Aerodynamics Summary Tables 46
7.1.3 Spanwise Aerodynamics, with Charts 49
7.1.4 Integrated Aerodynamics, C_D vs. C_L and C_L vs. α 49
7.2 Analysis Procedure: Start-to-Finish Example 49
7.2.1 Airplane Geometry Definition 49
7.2.2 Section Variant Analyses 50
7.2.3 MVL-15 Setup and Execution 50
7.2.4 Results Assessment 50
8.0 Validation Results 51
8.1 Available 2d-Geometry and 2d-Aerodynamics Tables 51
8.2 Airfoil and Wing Aerodynamics: Parameter Variations and 2d-Correlations 61
8.3 Airfoil and Wing Aerodynamics: Varying the Wing Geometry and 2d-Properties 64
8.4 Airfoil Flap Geometry and Aerodynamics 74
8.5 The 2d-Aerodynamics Adjustment Model 78
8.6 Generalized Validations: Wing Geometry, Aerodynamics, and Induced Drag 83
8.7 Aerodynamics Validation: Two Wings with Varying Relative Positions 95
8.8 Analysis Procedure: Airplane Takeoff and Approach Example 99
References 105

List of Tables

Table 1. File *in_2d_geom.txt*: Definitions and Format of the Airfoil Geometry File ……..9
Table 2. File *in_2d_geom.txt*: Geometry Tables, Airfoil Example……...……....10
Table 3. File *in_2d_geom.txt*: Geometry Tables, Wing Example……..…11
Table 4. File *in_2d_aero.txt*: Definitions and Format of the Aerodynamics Tables…….13
Table 5. File *in_2d_aero.txt*: Aerodynamics Tables, Airfoil Example……..……14
Table 6. File *in_2d_aero.txt*: Aerodynamics Tables, Wing Example…….……..15
Table 7. File *in_alphas.txt*: Angle Definitions, Airfoil and Wing Examples…….……17
Table 8. File *in_analysis.txt*: Analysis Definitions, Airfoil and Wing Examples……..…19
Table 9. File *in_wing1x.txt*: Wing and Lattice Geometry Format…….……21
Table 10. File *in_wing1x.txt*: Wing and Lattice Geometry Definitions……..……22
Table 11. File *in_wing1x.txt*: Wing and Lattice Geometry Airfoil Example…….……..23
Table 12. File *in_wing1x.txt*: Wing and Lattice Geometry Wing 1 Example…….…….24
Table 13. File *in_wing2x-5x.txt*: Wing and Lattice Geometry, Wing 2 Example……..…25
Table 14. File *out_aero.txt*: Integrated Aerodynamics Output Definitions…….……..27
Table 15. File *out_aero.txt*: Integrated Aerodynamics, Airfoil Example…….……28
Table 16. File *out_aero.txt*: Integrated Aerodynamics, Wing Example..…….……29
Table 17. File *out_span.txt*: Spanwise Aerodynamics Output Definitions…….……..30
Table 18. File *out_span.txt*: Spanwise Aerodynamics, Airfoil Example…….……31
Table 19. File *out_span.txt*: Spanwise Aerodynamics, Wing Example……..……32
Table 20. File *out_geom.txt*: Geometry Output Definitions……..……33
Table 21. File *out_geom.txt*: Geometry, Airfoil Example……..……...34
Table 22. File *out_geom.txt*: Geometry, Wing Example……..……35
Table 23. File *out_xzang.txt*: Geometry Subset Output Definitions……..……36
Table 24. File *out_xzang.txt*: Geometry Subset, Airfoil Example……..……37
Table 25. File *out_xzang.txt*: Geometry Subset, Wing Example……..……..38
Table 26. Wing Geometry Setup Example ……..……41
Table 27. Wing Geometry Setup Example: Takeoff Flaps ……..……42
Table 28. Wing Geometry Setup Example: Approach Flaps ……..……43
Table 29. Available Validation Files: Airfoil Geometry and 2d-Aerodynamics Information ……..……52
Table 30. Airfoil and Wing Aerodynamics: Varying the Lattice Geometry, αzl, δsi, and 3d-α ..……....62
Table 31. Airfoil and Wing Aerodynamics: Varying the Section Properties, c_o, $c_{f,}$ and *npanels*.……..…...65

Table 32. Aerodynamics of a Wing with Two Panels: Varying c_o, c_f, and $C_{l\alpha}$ ……..……...….69
Table 32. Aerodynamics of a Wing with Two Panels: Varying c_o, c_f, and $C_{l\alpha}$ (continued)..……...……...70
Table 33. Alternate Analysis Strategies: Lift Coefficient Results Comparison……....73
Table 34. Section Aerodynamic Results for Selected Flap Geometry Configurations …….76
Table 35. Section Aerodynamics Model Parameter Values ……..……81
Table 36. Aerodynamics of Two Wings: Varying the Relative LE Positions, α, and αzl……..…..96

List of Figures

Figure 1. Airplane layout and wing parameters..……..……..……...40
Figure 2. Airfoil parameters: section incidence and flaps..……..……..……....45
Figure 3. MVL-15 *3d-Results Presentation Utility* (airplane takeoff example)..……..……..……...48
Figure 4. Airfoil geometry comparisons: airfoil and flat plate variants. ……...53
Figure 5. Section geometry comparisons: MVL-15 (2d) nominal, takeoff, and approach. ……...54
Figure 6. Example airfoil aerodynamics, p0, p1, and p7 variants..…….....55
Figure 7. Example airfoil aerodynamics, αzl = 0.0 degrees..……..……..…….56
Figure 8. Example airfoil aerodynamics, αzl = -2.9 degrees..……..……..…….57
Figure 9. Example airfoil aerodynamics, f0, f29, and f6 flat-plate sections.……...……...…..58
Figure 10. Example airfoil aerodynamics, takeoff flaps.……..…59
Figure 11. Example airfoil aerodynamics, approach flaps.……..……60
Figure 12. Geometry illustration for the validation cases listed in Table 31..……..……...66
Figure 13. Spanwise lift for the validation cases listed in Table 31.……..……67
Figure 14. Geometry illustration for the validation cases listed in Table 32.……...…...71
Figure 15. Spanwise lift for the validation cases listed in Table 32.…….....72
Figure 16. Airfoil geometry comparisons: 2d-Variants Utility, MVL-15 (2d), and MVL-15 (3d).....75
Figure 17. Airfoil flap $\Delta\alpha zl$ / δ_f, validation..……..……..……...77
Figure 18. Airfoil aerodynamics model, incidence angle modifications..……..……..…….....79
Figure 19. Airfoil aerodynamics model, flap modifications..……..……..…….....80
Figure 20. Airfoil aerodynamics modifications, maximum limits..……..……..……...82
Figure 21. Two-panel wing: AR=8, TR=.25, dihedral=0.0/0.0 deg, sweep 0.0/0.0 deg..……..…….....84
Figure 22. Two-panel wing: AR=8, TR=.25, dihedral=0.0/0.0 deg, sweep 8.6/8.6 deg..……..…….....85
Figure 23. Two-panel wing: AR=8, TR=.25, dihedral=6.0/6.0 deg, sweep=0.0/0.0 deg..……..……....86
Figure 24. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep 8.6/0.0 deg..……..……....87
Figure 25. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep=0.0/8.6 deg..……..…….....88
Figure 26. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep=8.6/8.6 deg..……..……....89
Figure 27. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep=8.6/17.2 deg..……..…….....90
Figure 28. Elliptic wing spanwise lift, C_l (2y/b), as f (AR = 6, 8, 10, 12), ntip=0..……..……..…….....91
Figure 29. Spanwise lift, C_l (2y/b), as f (TR, AR = 6, 8, 10, 12), ntip=0..……..……..…….....92
Figure 30. C_{Di} comparisons as f (AR, TR)..……..……..……...93
Figure 31. Spanwise lift, C_l (2y/b), TR=0.125, AR=8, tip comparison (ntip=0, ntip=4)..……..…….....94
Figure 32. Figure to illustrate the geometry listed in Table 36.……..……...……....97

Figure 33. Spanwise lift for the validation cases listed in Table 36.……..……...98
Figure 34. Airplane takeoff geometry..…….…….……..…..…....100
Figure 35. Airplane approach geometry..…….…….……..……...101
Figure 36. Airplane takeoff and approach spanwise lift, C_l (2y/b)..…….…….…….....102
Figure 37. Airplane takeoff and approach drag polars, C_D vs. C_L..…….…….……....103
Figure 38. Airplane takeoff and approach lift curves, $C_{L\alpha}$.…….…….……104

1.0 Introduction

MVL-15 is the most recent version of the Modified Vortex-Lattice (MVL) code developed within the Aerodynamics Systems Analysis Branch (ASAB) at NASA LaRC. The term "modified" refers to the primary modification of the core vortex-lattice methodology: inclusion of viscous aerodynamics tables that are linked to the linear solution via iterative processes. The inclusion of the viscous aerodynamics inherently converts the MVL-15 from a purely analytic linearized method to a semi-empirical blend which retains the rapid execution speed of the linearized method while empirically characterizing the section aerodynamics at all spanwise lattice points. The modification provides a means to assess non-linear effects on lift that occur at angles of attack near stall, and provides a means to determine the drag associated with the application of design strategies for lift augmentation such as the use of flaps or blowing. The MVL-15 code is applicable to the analyses of aircraft aerodynamics during cruise, but it is most advantageously applied to the analysis of aircraft operating in various high-lift configurations.

The MVL methodology has been previously conceived and implemented; the initial concept version was delivered to the ASAB in 2001 (van Dam, C.), subsequently revised (Gelhausen, P. and Ozoroski, T. 2002 / AVID Inc., Gelhausen, P., and Roberts, M. 2004), and then overhauled (Ozoroski, T., Hahn, A. 2008). The latest version, MVL-15 has been refined to provide analysis transparency and enhanced to meet the analysis requirements of the Environmentally Responsible Aviation (ERA) Project. Each revision has been implemented with reasonable success. Separate applications of the methodology are in use, including a similar in-house capability, developed by Olson, E. that is tailored for structural and acoustics analyses.

A central premise of the methodology is that viscous aerodynamic data can be associated with analytic inviscid aerodynamic results at each spanwise wing section, thereby providing a pathway to map viscous data to the inviscid results. However, a number of factors can sidetrack the analysis consistency during various stages of this process. For example, it should be expected that the final airplane lift curve and drag polar results depend strongly on the geometry and aerodynamics of the airfoil section; however, flap deflections and flap chord extensions change the local reference geometry of the input airfoil, the airplane wing, the tabulated non-dimensional viscous aerodynamics, and the spanwise links between the linear and the viscous aerodynamics. These changes also affect the bound circulation and therefore, calculation and integration of the induced angle of attack and induced drag. MVL-15 is configured to ensure these types of challenges are properly addressed.

This report is a comprehensive manual describing the theory, use, and validation of the MVL-15 analysis tool. Section 3 summarizes theoretical, procedural, and characteristic features of MVL-15, and includes a list of the files required to setup, execute, and summarize an analysis. Section 4, Section 5, Section 6, and Section 7 combine to comprise the *User's Guide* portions of this report. The MVL-15 input and output files are described in Section 4 and Section 5, respectively; the descriptions are supplemented with example files and information about the file formats, parameter definitions, and typical parameter values. Section 6 describes the *Wing Geometry Setup Utility* and the *2d-Variants Utility* files that simplify and assist setting up a consistent set of MVL-15 geometry and aerodynamics input parameters and input files. Section 7 describes the use of the *3d-Results Presentation Utility* file that can be used to automatically create summary tables and charts from the MVL-15 output files. Section 8 documents the *Validation Results* of an extensive and varied validation test matrix, including results of an airplane analysis representative of the ERA Program. A start-to-finish example of the airplane analysis procedure is described in Section 7.

2.0 Symbols

2d – 2-Dimensional, i.e., Airfoil, Wing Section, or Infinite Wing

2y/b – Non-Dimensional Spanwise Distance from Wing Root = 0

3d – 3-Dimensional, i.e., Wing Planform or Aircraft Configuration

b – Wing Span

c – Airfoil or Wing Chord Length

C_d, C_D – Coefficient of Drag (2d, 3d)

C_{df}, C_{Df} – Coefficient of Skin Friction Drag (2d, 3d)

C_{Di} – Coefficient of Induced Drag (3d)

C_{do}, C_{Do} – Minimum Coefficient of Drag (2d, 3d)

c_o – Nominal Chord Length, Measured LE to TE with Flaps Retracted (2d)

c_{flap} – Projected Chord Length, Flaps Extended (3d)

c_{fp} – Projected Chord Length, Flaps Extended (2d)

c_{fr} – Retracted Flap Fraction of the Nominal Chord Length (2d)

c_{fx} – Retracted Flap Multiplier, as Extended (2d)

c_{fxr} – Resultant Chord Length, Flaps Extended (2d)

C_l, C_L – Coefficient of Lift (2d, 3d)

$C_{l\alpha}$, $C_{L\alpha}$ – Slope of the 3d Lift Curve (2d, 3d)

C_{lmax}, C_{Lmax} – Maximum Coefficient of Lift (2d, 3d)

c_t, c_{tip} – Tip Chord Length

S_w – Wing Area

w – Reference to a *wing*

X, x –Streamwise Coordinate Axis, Streamwise Coordinate

Y, y – Spanwise Coordinate Axis, Spanwise Coordinate

Z, z –Vertical Coordinate Axis, Vertical Coordinate

Greek Symbols

α – Angle of Attack, degrees

α_i – Induced Angle of Attack, degrees

α_{max} – Angle of Attack for Maximum Lift, degrees (2d)

αzl – Angle of Attack for Lift=0 (i.e., *alpha-zero-lift*), degrees (2d)

$\Delta\alpha$ – Change in Angle of Attack, degrees (2d, 3d)

δ_f, δ_{flap}, df – Flap Deflection Angle, degrees (2d)

δ_{si}, dsi – Change in Section Incidence Angle, degrees (2d)

Abbreviations

ain – Reference to *Approach Inboard Flaps*

aout – Reference to *Approach Outboard Flaps*

AR – Wing Aspect Ratio

ASAB – Aeronautics Systems Analysis Branch

deg – Degrees

ERA – Environmentally Responsible Aviation Project

f – Flat Plate Section Incidence Designation (i.e., f 1 = +1.0 degrees)

ft – Feet

LE – Leading Edge of an Airfoil or Wing Section

MVL – Modified Vortex Lattice

non-dim – Non-Dimensional

ntip – Number of Wing Tip Points (= *nallow*, file: *in_wing*x.txt*)

p – Section Incidence Variant Designation (i.e., p1 = nominal +1.0 degrees)

npanels – Reference to the *Number of Wing Panels*

ref – Reference Length or Area (i.e., c_{ref} = reference chord)

tki – Reference to *Takeoff Inboard Flaps*

tko – Reference to *Takeoff Outboard Flaps*

TE – Trailing Edge of an Airfoil or Wing Section

TR – Wing Taper Ratio

3.0 Modified Vortex Lattice

3.1 Background Theory

A *M*odified *V*ortex *L*attice method (MVL-15) has been developed which includes a method to link the inviscid analytic results at spanwise wing locations to empirically-derived viscous aerodynamic data. Normally outside the scope of vortex-lattice codes, the viscous modifications extend the analysis application to include non-linear effects occurring at high lift conditions. The code accepts parameterized airfoil and wing geometry inputs, including camber, twist, angle of attack, dihedral, sweep, and taper. A total of five wings, each with five different section properties can be modeled. Details of these capabilities will be presented throughout this report. An overview of the nominal vortex-lattice-methodology is provided in following paragraphs; further details about the assumptions, limitations, and mathematics of the methodology are available in References 1, 2, and 3.

The vortex lattice method is based on the thin-airfoil-theory assumption that the wing circulation can be modeled as individual horseshoe vortices (comprised of bound vortex and trailing vortices) distributed on the wing as a lattice extending in the chordwise and spanwise directions. The individual vortices are positioned at the ¼ chord location of each lattice element, and control points are positioned at the ¾ chord location of each lattice element. Mathematically, the relative positions of the lattice vortices and control points can be represented as a square matrix of influence coefficients. If the vortex strengths were known, then the downwash, and therefore circulation and lift, could be calculated at each control point according to the Biot-Savart law and by solving the system of equations generated by multiplying the influence coefficient matrix by the column matrix of vortex strengths. However, the vortex strengths are not known a-priori, so it is necessary to retain the column matrix of vortex strengths as a set of variables.

Considered from an aerodynamics perspective, the free stream velocity can not flow through the wing lattice points in a direction perpendicular to the wing; therefore, it must be offset by an equal and opposite downwash velocity. In accordance with thin airfoil theory, the free stream velocity can be set to unity and the no-flow boundary condition can be calculated as the sine of the wing incidence angle at each control point. Representing the boundary conditions at each lattice control point as a column matrix, the vortex strengths can be calculated as the product of the inverted relative position matrix and the control point boundary condition matrix.

Once the matrix operations have been completed and the vortex strengths have been determined, the chordwise vortex strengths can be summed at each wing spanwise section. The wing lift is calculated based on an area-weighted summation (integration) of the spanwise lift. The MVL-15 *out_aero.txt* file lists both the area-weighted and the (un-weighted) average lift coefficients as output to provide insight to the efficiency of the wing spanwise lift distribution. As the efficiency of the wing spanwise lift distribution increases, the difference between the weighted and average lift coefficients decreases.

The MVL-15 methodology associates the section viscous lift and drag coefficients C_l, and C_d, based on the section incidence angle, δ_{si}, determined by the analytic vortex lattice result of a given iteration (the sum of angle of attack, α, induced angle of attack, α_i, and geometry). Consider a case that a single airfoil is specified for use along the entire span of a wing, and that the viscous lift and drag of the airfoil are known as a function of the airfoil incidence angle. Also, assume that inviscid vortex lattice results provide the vortex strengths, the lift, the induced angle of attack, and the induced drag at each spanwise station of the wing. By reference to the the incidence angles of the airfoil and the wing sections, the airfoil viscous aerodynamics could be mapped to each wing section. The mapping could then be used to revise the wing section aerodynamics and could be integrated across the span to obtain the wing viscous aerodynamics.

Once the spanwise lift coefficient substitutions have been implemented, the induced angle of attack, the bound circulation of the wing, and the boundary conditions of the vortex lattice solution will change. The influence coefficient matrix, which is a function of relative geometry only, remains unaffected by these changes. However, the revised boundary conditions change the vortex strength calculations, the inviscid spanwise lift results, and the associated links to the viscous aerodynamics tables. The recursive dependence of these parameters dictates using an iterative approach to obtain the final viscous aerodynamics solution. The MVL-15 iteration proceeds in the following manner:

1. Calculate the spanwise circulation
2. Calculate the spanwise induced angle of attack
3. Calculate the section incidence angle
4. Substitute viscous section aerodynamics at the section incidence angle
5. Check for convergence and output results, or continue to *step 6*
6. Calculate a new spanwise induced angle of attack based on viscous circulation
7. Modify the spanwise incidence angles with the new induced angles of attack
   (this modifies the boundary condition of the matrix equation)
8. Solve the linear system of equations using the modified boundary condition
9. Continue until convergence in each spanwise section is achieved.
10. Check for convergence and output results, or return to *step 6*

Note that both one-dimensional column matrices representing the vortex strengths and the control point incidence angles could change prior to subsequent re-calculation of the matrix. However, the functional dependence between vortex strength and induced angle of attack, enables the iterative solution, and eliminates the need to vary both parameters to obtain proper convergence and a unique solution. The method can be shown to reduce to a standard vortex lattice method if inviscid section coefficients are input to the viscous aerodynamics table. A significant number of validation tests are provided in this report to verify this iteration scheme and the strategy linking inviscid and viscous aerodynamics.

Convergence difficulties can arise during the analysis of various wing planforms when differences between the inviscid and viscous bound circulation and lift curve slopes (at a given section incidence angle) induce downwash angles that alternate between high and low values. This is most prominent during analyses at angles of attack near stall and for planforms which generate upwash at the tip thereby generating localized incidence angles near or above stall. In similar situations that eventually do converge, the number of iterations can lead to time-consuming analyses. All three of these concerns are eliminated within the MVL-15 analysis code.

Several input factors in the *in_2d_aero.txt* file limit and penalize attempts to access and link viscous data to extreme inviscid incidence angles. Additionally, MVL-15 features a boundary condition model that alters the inviscid vortex lattice solution at the wing-tip. The model adds a hypothetical control point one lattice position outboard of the wing tip and enforces a zero-lift condition at the hypothetical point. The lattice solution is then adjusted inboard of the wing tip to account for the influence of the boundary condition, based on the user-defined input, *nallow* (file: *in_wing*x.txt*). As implemented, changes to the original lift distribution are concentrated at the wing-tip. The model forces rapid convergence and is applicable to analyses which include winglets.

3.2 Scope

The MVL-15 analysis tool is intended for aerodynamic analysis applications during the conceptual design phase. The tool can be setup for either inviscid or viscous aerodynamic analyses, and is suitable for the analysis of two-dimensional airfoil sections and various aircraft configurations. Appropriate use of the section aerodynamics tables provides the capability to analyze lift augmentation through the use of flaps or blowing.

3.3 Required Files

The Fortran-90 programming language was utilized to encode the modified vortex-lattice methodology and develop the MVL-15 computational analysis tool. *Compaq Visual Fortran Version 6.6* was used for developing, compiling, and executing MVL-15. The following files are required for executing MVL-15:

- *MVL-15.exe*

- *in_2d_aero.txt*
- *in_2d_geom.txt*
- *in_alphas.txt*
- *in_analysis.txt*
- *in_wing1x.txt*
- *in_wing(2x-5x).txt*

- *out_aero.txt*
- *out_span.txt*
- *out_geom.txt*
- *out_xzang.txt*
- *out_diag.txt*

All analyses presented in this report were completed using a single personal computer (64-bit operating system, with a 2.50 GHz processor, and 16.0 GB RAM).

3.4 Setup and Analysis Files

The initial steps of an airplane analysis include parametrically defining the general layout of the airplane wing and horizontal stabilizer, the wing planform geometry, and the wing flap chord geometry. The section geometry and aerodynamics of the airfoils sections associated with the airplane nominal, takeoff flaps, and approach flaps configurations also must be specified. The *Wing Geometry Setup Utility* and *2d-Variants Utility* guide the setup, provide feedback, and facilitate consistent parameter definitions throughout the course of the analysis; the functionality is described in more detail in Section 6.

The results generated from execution of the MVL-15 analysis code are tabulated and saved as text files. For improved visualization and analysis presentation, the MVL-15 *3d-Results Presentation Utility* can be used to automatically generate a set of summary tables and charts. Additional details about the functionality and capabilities of this file are provided in Section 7.

4.0 Input File Examples, Definitions, and Formats

Section 4 provides information about the general format, parameter definitions, and typical parameter values associated with each of the MVL-15 *input.txt* files. Section 4 also provides example input files suitable for airfoil and wing analyses, modified only to the extent required for presentation in this report. The following sections describe the functionality of these input files in more detail.

4.1 Input File: *in_2d_geom.txt*

The general format, parameter definitions, and typical parameter values of the *in_2d_geom.txt* file are shown in Table 1. Example input files suitable for airfoil and wing analyses are provided in Table 2 and Table 3, respectively. The *in_2d_geom.txt* file is the basis for all airfoil analyses, as it defines the coordinates and slope of the airfoil mean camber line at 41 chordwise points (or, every 2.5% chord). For wing analyses, the section geometry and the influence of the section camber on the lattice geometry are replaced by the influence of the associated 2d-aerodynamics table, which inherently contains the incidence angle attributable to camber.

It is important to note that separate section geometry files must be provided for each wing panel, even if successive spanwise wing sections are associated with identical airfoils and 2d-aerodynamics tables. To ensure consistency throughout the airfoil, wing, and airplane analysis process, the MVL-15 geometry setup and analysis files, *Wing Geometry Setup Utility* and *2d-Variants Utility* should be utilized. Descriptions and information about these files will be provided in Section 6.1 and Section 6.2.

4.2 Input File: *in 2d geom variation template.txt*

The *in 2d geom variation template.txt* input file provides the capability to automatically generate, name, and save unique *in_2d_geom.txt* geometry files. The format of this file is identical to the 2d-geometry file of Table 2. When generating wing section variants, the template file is automatically copied and updated to reflect the variant geometry and description. This file can be accessed indefinitely, and must be available in the same directory as the *2d-Variants Utility*.

Table 1. File *in_2d_geom.txt*: Definitions and Format of the Airfoil Geometry File

Section Index Order:

index = 1	wing 1, panel 1
index = 2	wing 1, panel 2 ...
index = n1	wing 1, panel n1
index = n1+1	wing 2, panel 1 ...
index = n1+n2	wing 2, panel n2
etc..	
index = n1+n2+n3+n4 +1	wing 5, panel 1...
index = n1+n2+n3+n4+n5	wing 5, panel n5

in_2d_geom.txt (definitions)

Input	Description
header	required header: "label"
index	section index (max=9)
name	optional header: "description"
nRows	number of data rows (max =41)
x/c	non-dimensional chordwise dimension
z/c	non-dimensional thickness dimension
dz/dx	slope of the airfoil mean camber at x/c

in_2d_geom.txt (general format)

header	index	name (max 140 characters)		
section	*1*	*p0dsi_LE_0df_pt0cfr_1pt0cfx_0ds_valid15*		
nRows				
41				
x/c		**z/c**		**dz/dx**
x/c (1)		*z/c (1)*		*dz/dx (1)*
to		to		to
x/c (41)		*z/c (41)*		*dz/dx (41)*
section	*2*	*p1dsi_LE_0df_pt0cfr_1pt0cfx_0ds_valid15*		
41				
x/c (1)		*z/c (1)*		*dz/dx (1)*
to		to		to
x/c (41)		*z/c (41)*		*dz/dx (41)*
	etc...			
section	*9*	*p7dsi_LE_0df_pt0cfr_1pt0cfx_0ds_valid15*		
41				
x/c (1)		*z/c (1)*		*dz/dx (1)*
to		to		to
x/c (41)		*z/c (41)*		*dz/dx (41)*

Table 2. File *in_2d_geom.txt*: Geometry Tables, Airfoil Example

```
section   1          p1dsi_LE_0df_pt0cfr_1pt0cfx_0ds_valid15
41
  0.00000           0.00000           0.08254
  0.02500           0.00191           0.07629
  0.05000           0.00366           0.07004
  0.07500           0.00525           0.06379
  0.10000           0.00669           0.05754
  0.12500           0.00797           0.05129
  0.15000           0.00910           0.04504
  0.17500           0.01007           0.03879
  0.20000           0.01088           0.03254
  0.22500           0.01154           0.02629
  0.25000           0.01204           0.02004
  0.27500           0.01239           0.01379
  0.30000           0.01258           0.00754
  0.32500           0.01261           0.00129
  0.35000           0.01248          -0.00496
  0.37500           0.01220          -0.01121
  0.40000           0.01177          -0.01746
  0.42500           0.01126          -0.02023
  0.45000           0.01069          -0.02301
  0.47500           0.01004          -0.02579
  0.50000           0.00933          -0.02857
  0.52500           0.00858          -0.02996
  0.55000           0.00776          -0.03273
  0.57500           0.00687          -0.03551
  0.60000           0.00592          -0.03829
  0.62500           0.00489          -0.04107
  0.65000           0.00379          -0.04384
  0.67500           0.00263          -0.04662
  0.70000           0.00139          -0.04940
  0.72500           0.00009          -0.05218
  0.75000          -0.00129          -0.05496
  0.77500          -0.00273          -0.05773
  0.80000          -0.00424          -0.06051
  0.82500          -0.00582          -0.06329
  0.85000          -0.00748          -0.06607
  0.87500          -0.00920          -0.06884
  0.90000          -0.01099          -0.07162
  0.92500          -0.01285          -0.07440
  0.95000          -0.01478          -0.07718
  0.97500          -0.01678          -0.07996
  1.00000          -0.01884          -0.08273
```

Table 3. File *in_2d_geom.txt*: Geometry Tables, Wing Example

```
section   1          P1df10cfr18cfx120tki
41
  0.000              0.0000             0.0825
  0.024              0.0018             0.0763
  0.048              0.0034             0.0700
   etc.                etc.               etc.
  0.944             -0.0286            -0.2026
  0.972             -0.0339            -0.2268
  1.000             -0.0397            -0.2515

section   2          P1df15cfr15cfx140tko
41
  0.000              0.0000             0.0825
  0.024              0.0018             0.0763
  0.048              0.0034             0.0700
   etc.                etc.               etc.
  0.938             -0.0302            -0.2508
  0.969             -0.0375            -0.2964
  1.000             -0.0457            -0.3451

section   3          p1dsi_0df_pt0cfr_1pt0cfx_0ds_valid15
41
 0.0000              0.0000             0.0825
 0.0237              0.0017             0.0763
 0.0475              0.0032             0.0700
   etc.                etc.               etc.
 0.950              -0.0148            -0.0772
 0.975              -0.0168            -0.0800
 1.000              -0.0188            -0.0827

   etc.

section   9          p1dsi_0df_pt0cfr_1pt0cfx_0ds_valid15
41
  0.000              0.0000             0.0825
  0.025              0.0019             0.0763
  0.050              0.0037             0.0700
   etc.                etc.               etc.
  0.950             -0.0148            -0.0772
  0.975             -0.0168            -0.0800
  1.000             -0.0188            -0.0827
```

4.3 Input File: *in_2d_aero.txt*

The general format, parameter definitions, and typical parameter values of the *in_2d_aero.txt* file are shown in Table 4. Example input files suitable for airfoil and wing analyses are provided in Table 5 and Table 6, respectively. The *in_2d_aero.txt* file is comprised of 2d-aerodynamics tables and several control parameters that influence how MVL-15 accesses and manipulates the tabulated values during execution. Separate tables and control parameters must be included for each wing panel of the analysis.

Each row of the table lists the angle of attack in column 1, the lift coefficient in column 2, and the drag coefficient in column 3, in descending order, by increasing angle of attack values. The number of data points selected from a reference source for inclusion to the 2d-aerodynamics tables is not critical. However, relatively more points should be included as the lift curve becomes non-linear. Two important requirements are that the lift curve slope must increase monotonically to the point of stall, and that one row of the table must list the angle of attack at which the lift is zero, αzl (i.e., *alpha-zero-lift*). Each angle of attack is listed with the corresponding lift coefficient, C_l, and drag coefficient, C_d values. The control parameters in this file extend and limit the range of values of the nominal table; and apply penalties if additional extrapolation is indicated by the inviscid results of a given iteration. This is especially important when the inviscid results at a section indicate the need to access the 2d-aerodynamics table at angles of attack outside the tabulated range.

Although the 2d-aerodynamics table functions to apply viscous effects to the inviscid result, the user may choose to specify a linear lift curve, eliminate angles that include stall onset, or set the the tabulated values of skin friction drag to zero. The flexibility to adjust the 2d-aerodynamics table in this way is useful during the initial analysis phase when assessing various airfoils, wings, and airplane configurations.

Table 4. File *in_2d_aero.txt*: Definitions and Format of the Aerodynamics Tables

Section Index Order:

index = 1	wing 1, panel 1
index = 2	wing 1, panel 2 ...
index = n1	wing 1, panel n1
index = n1+1	wing 2, panel 1 ...
index = n1+n2	wing 2, panel n2
etc..	
index = n1+n2+n3+n4 +1	wing 5, panel 1...
index = n1+n2+n3+n4+n5	wing 5, panel n5

in_2d_aero.txt (definitions)

Input	Description
index	Wing panel index
n2dpt	Number of 2d viscous data rows (max=30)
ncl = 0	Row number containing cl=0 (req'd data pt)
extlow	Input value (deg) to extrapolate below $\alpha(1)$
ext+hi	Input value (deg) to extrapolate above α(n2dpt)
extloss	Loss factor if $\alpha <$ extlow or if $\alpha >$ ext+hi
azlist	Tabulated zero-lift angle and 2d reference angle
name	Optional header: airfoil description or filename
α	Tabulated angle of attack (deg)
cl	Tabulated viscous lift coefficient
cd	Tabulated viscous drag coefficient
cm	Placeholder (required) moment coefficient

in_2d_aero.txt (general format)

index						
1						
(Headers start...						*Description 1 ...end)*
n2dpt	**ncl = 0**	**extlow**	**ext+hi**	**extloss**	**azlist**	*P1df10cfr18cfx120tki*
7	*1*	*-3.0*	*4.0*	*1.0*	*-2.9232*	
α		**cl**		**cd**		**cm**
α(1)		*0.000*		*cd(1)*		*cm(1)*
to		*to*		*to*		*to*
α(7)		*cl(7)*		*cd(7)*		*cm(7)*
2						
n2dpt	**ncl = 0**	**extlow**	**ext+hi**	**extloss**	**azlist**	*P1df15cfr15cfx140tko*
8	*2*	*-1.0*	*5.0*	*1.0*	*-2.9232*	
α		**cl**		**cd**		**cm**
α(1)		*cl(1)*		*cd(1)*		*cm(1)*
α(2)		*0.000*		*cd(2)*		*cm(2)*
to		*to*		*to*		*to*
α(8)		*cl(8)*		*cd(8)*		*cm(8)*
			etc...			
9						
n2dpt	**ncl = 0**	**extlow**	**ext+hi**	**extloss**	**azlist**	*P1df0cfr0cfx1_visc*
5	*1*	*-3.0*	*3.0*	*1.0*	*-2.9232*	
α		**cl**		**cd**		**cm**
α(1)		*0.000*		*cd(1)*		*cm(1)*
to		*to*		*to*		*to*
α(5)		*cl(5)*		*cd(5)*		*cm(5)*

Table 5. File *in_2d_aero.txt*: Aerodynamics Tables, Airfoil Example

1

n2dpt	**ncl = 0**	**extlow**	**ext+hi**	**extloss**	**azlist**	*P1df0cfr0cfx1_invs*
14	1	-3.0	2.0	1.2	-2.9232	
-2.9232		0.0000		0.0000		-0.30
-2.0000		0.1012		0.0000		-0.30
-1.0000		0.2109		0.0000		-0.30
0.0000		0.3206		0.0000		-0.30
1.0000		0.4302		0.0000		-0.30
2.0000		0.5399		0.0000		-0.30
3.0000		0.6496		0.0000		-0.30
5.0000		0.8689		0.0000		-0.30
6.0000		0.9785		0.0000		-0.30
7.0000		1.0882		0.0000		-0.30
9.0000		1.3075		0.0000		-0.30
11.0000		1.5268		0.0000		-0.30
12.0000		1.6365		0.0000		-0.30
13.0000		1.7462		0.0000		-0.30

2

n2dpt	**ncl = 0**	**extlow**	**ext+hi**	**extloss**	**azlist**	*P1df0cfr0cfx1_visc*
14	1	-3.0	4.0	1.2	-2.9232	
-2.9232		0.0000		0.0105		-0.30
-2.0000		0.1012		0.0089		-0.30
-1.0000		0.2109		0.0075		-0.30
0.0000		0.3206		0.0065		-0.30
1.0000		0.4302		0.0058		-0.30
2.0000		0.5399		0.0054		-0.30
3.0000		0.6495		0.0054		-0.30
5.0000		0.8689		0.0064		-0.30
6.0000		0.9785		0.0075		-0.30
7.0000		1.0882		0.0088		-0.30
9.0000		1.2682		0.0119		-0.30
11.0000		1.4082		0.0149		-0.30
12.0000		1.4582		0.0161		-0.30
13.0000		1.4782		0.0166		-0.30

Table 6. File *in_2d_aero.txt*: Aerodynamics Tables, Wing Example

```
   1
  n2dpt      ncl = 0      extlow      ext+hi      extloss      azlist     P1df10cfr18cfx120tki"
    14           1        -3.0         3.0          1.2      -2.9230
-3.4716                  0.0000                   0.0667                  -0.30
 1.6617                  0.6564                   0.0451                  -0.30
   etc.                    etc.                     etc.                    etc.
14.3142                  2.0171                   0.0552                  -0.30

   2
  n2dpt      ncl = 0      extlow      ext+hi      extloss      azlist     P1df10cfr18cfx120tki"
    14           1        -3.0         3.0          1.2      -2.9232
-3.4716                  0.0000                   0.0667                  -0.30
 1.6617                  0.6564                   0.0451                  -0.30
   etc.                    etc.                     etc.                    etc.
14.3142                  2.0171                   0.0552                  -0.30

   3
  n2dpt      ncl = 0      extlow      ext+hi      extloss      azlist     P1df15cfr15cfx140tko"
    14           1        -3.0         3.0          1.2      -2.9232
-5.0888                  0.0000                   0.0767                  -0.30
 1.5769                  0.8937                   0.0515                  -0.30
   etc.                    etc.                     etc.                    etc.
13.6433                  2.2545                   0.0746                  -0.30

   4
  n2dpt      ncl = 0      extlow      ext+hi      extloss      azlist     P1df15cfr15cfx140tko"
    14           1        -3.0         3.0          1.2      -2.9232
-5.0888                  0.0000                   0.0767                  -0.30
 1.5769                  0.8937                   0.0515                  -0.30
   etc.                    etc.                     etc.                    etc.
13.6433                  2.2545                   0.0746                  -0.30

  etc.

   7
  n2dpt      ncl = 0      extlow      ext+hi      extloss      azlist     P1df0cfr0cfx1_visc
    14           1        -3.0         4.0          1.2      -2.9232
-2.9232                  0.0000                   0.0105                  -0.30
-2.0000                  0.1012                   0.0089                  -0.30
   etc.                    etc.                     etc.                    etc.
13.0000                  1.4782                   0.0166                  -0.30
```

4.4 Input File: *in_alphas.txt*

The general format, parameter definitions, and typical parameter values of the *in_alphas.txt* file are shown in Table 7. Example input files suitable for airfoil and wing analyses also are provided.

For airfoil analyses, the user should specify a single angle of attack, set to a value of 0.0, for wing-1. If multiple angles of attack, multiple wings, or non-zero angles of attack are specified, MVL-15 will reset the angle of attack inputs at the outset of execution. It should be noted that a properly formatted *in_alphas.txt* file is required, even if the input values are not within the expected parameter bounds. This eliminates the need to save separate input files when transitioning between 2d- and 3d- analyses, as the wing angles of attack are overwritten if the *kanlys* analysis parameter is set to an integer value of 2.

For wing or airplane configuration analyses, at least one angle of attack must be provided for each wing, and multiple angles of attack can be specified for use generating lift curves or drag polars. The ability to specify separate angles of attack for a wing-horizontal tail combination provides a method to adjust the lift on tail without the need to modify the airfoil section specified for the horizontal tail. It is not possible to specify separate angles of attack for individual panels of a wing; such adjustments must be accomplished by updating the airfoil properties associated with the section, as listed in the *in_2d_aero.txt* file.

Certain tables are created during the analysis of wing planforms or airplane configurations based on the value of the *alfput* input parameter. As properly specified, the value of the *alfput* parameter should match one of the angles of attack listed for wing-1, within a margin of +/- .10 degrees.

Table 7. File *in_alphas.txt*: Angle Definitions, Airfoil and Wing Examples

in_alphas.txt (definitions)

Input	Description
kanlys	Analysis Type: 3d Test, 2d Airfoil, or 3d Wing
nwings	Number of lifting wing surfaces (max=5)
nalpha	Number of angles for 3d polar (max=30, 2d=1)
alfput	Output geometry and spanwise aero at this angle
wing(n)	Angles of attack list for each wing(n)

in_alphas.txt (2d example)

```
" analysis type test:1 azl2d:2 wing3d:3                  kanlys "      2
" number of lifting 3d-wing surfaces:                    nwings "      1
" number of angles of attack per wing:                   nalpha "      1
" Output geom & 2yb at wing1 alpha of:                   alfput  "     0.0
"-----------------------------------------------------"
"       wing1       wing2       wing3       wing4       wing5
        0.0
```

in_alphas.txt (3d example)

```
" analysis type test:1 azl2d:2 wing3d:3                  kanlys "      3
" number of lifting 3d-wing surfaces:                    nwings "      2
" number of angles of attack per wing:                   nalpha "      17
" Output geom & 2yb at wing1 alpha of:                   alfput  "     6.0
"-----------------------------------------------------"
"       wing1       wing2       wing3       wing4       wing5
        0.0         -0.6
        1.0         -0.4
        2.0         -0.2
        etc...      etc...
        16.0        1.4
```

4.5 Input File: *in_analysis.txt*

The general format, parameter definitions, and typical parameter values of the *in_analysis.txt* file are shown in Table 8. Example input files suitable for airfoil and wing analyses also are provided.

Most of the parameters within this file are used to control the convergence and execution of MVL-15. For an airfoil analysis, a maximum of only two iterations are required to determine αzl of the geometry section. For a wing planform or airplane configuration, a maximum of 40 iterations will be attempted, as needed, before the result is output (whether or not it has converged) for that particular angle of attack. The maximum number of iterations can be increased to 100 if the *maxiter* and *itrovr* input parameter values are equal and if the value is greater than 40 and less than or equal to 100. Typically at each angle of attack, an airplane analysis requires about 10 iterations and can be completed in about 10 seconds.

Table 8. File *in_analysis.txt*: Analysis Definitions, Airfoil and Wing Examples

in_analysis.txt (definitions)

Input	Description
maxitr	maximum iterations per analysis angle of attack 2d: = 2 iterations 3d: <= 40 iterations, <=100 iterations with "itrovr"
itrovr	flag to increase the maximum iterations > 40, usage: "itrovr" = "maxitr" = desired maximum
ctoler	the aerodynamics solution (at alpha) is considered converged if cl(itr)-cl(itr-1) < "ctoler" for all spanwise points (ipts-nallow) of each 3d wing
xtoler	tolerance multiplier to relax convergence limit ctoler (itr+1) = ctoler(itr) * xtoler
nstuck	if the total number of converged points repeats for "nstuck" iterations: ctoler = ctoler * xtoler and "nstuck" counter (=0)
nctrip	resets the nstuck and nctrip counters (=0) after "nctrip" iterations (independent of "nstuck")
fstcnv	improves convergence performance: x(itr) = x(itr-1) + (x(itr)-x(itr-1))*fstcnv

in_analysis.txt (2d example)

" maximum number of iterations	**maxitr "**	10
" override maxitr, if = and >40	**itrovr "**	10
" initial cl convergence limit	**ctoler "**	0.0005
" delta cl convergence multiple	**xtoler "**	1.5
" trip if repeating unconverged	**nstuck "**	9
" trip after nloops unconverged	**nctrip "**	17
" iteration update .01< fc <.99	**fstcnv "**	0.7000

in_analysis.txt (3d example)

" maximum number of iterations	**maxitr "**	30
" override maxitr, if = and >40	**itrovr "**	10
" initial cl convergence limit	**ctoler "**	0.0001
" delta cl convergence multiple	**xtoler "**	2.0
" trip if repeating unconverged	**nstuck "**	4
" trip after nloops unconverged	**nctrip "**	7
" iteration update .01< fc <.99	**fstcnv "**	0.6667

4.6 Input File: *in_wing1x.txt*

The general format of the *in_wing1x.txt* file is shown in Table 9. Parameter definitions, units, and typical parameter values of the *in_wing1x.txt* file are shown in Table 10. An example *in_wing1x.txt* input file, suitable for the analysis of a single airfoil or wing section, is provided in Table 11. Examples of the *in_wing1x.txt* and *in_wing2x.txt* input files, suitable for the analysis of an airplane utilizing two lifting surfaces, are provided in Table 12 and Table 13, respectively. The format and content of the *in_wing1x.txt* and *in_wing2x.txt* input files are significantly different due to the presence of additional reference area and airplane configuration parameters in the *in_wing1x.txt* file. These files are most easily generated using the features and functionality of the *Wing Geometry Setup Utility* described in Section 6.1.

The wing area, an alternate reference area, and aspect ratio are listed in the *in_wing1x.txt* file. The wing area and aspect ratio are calculated internally based on the wing panel inputs listed at the lower section of the same file. As a result, the wing area and aspect ratio input values primarily represent expected values that can be compared to various MVL-15 outputs to ensure analysis consistency. The *Swaero* input parameter can be specified as either a positive or negative number, depending on whether the user intends to modify the *out_aero.txt* output file with an additional row of data. If the value is negative, the row will not be added, if the value is positive, the row will be added if the absolute value of the reference area difference (*Swgeo* – *Swaero*) is greater than 10.

The *npanels*, *ipts-k*, and *jpts-k* input parameters are used to specify the number of wing panels, spanwise lattice points, and chordwise lattice points covering *wing-k*. (The term *wing-k* is used to denote that separate wings of a configuration are modeled separately. Considering wing-1 as an example, *ipts-k* would refer to *ipts-1* and the number of spanwise stations on wing-1 would be specified in the *in_wing1x.txt* file.) The *nallow* input parameter is used to define the number of tip points used for modeling the lift at the wing tip. Because modifying the wing tip lift affects the nominal MVL-15 convergence scheme, the *nallow* parameter was implemented to dually indicate an allowance of the number of unconverged points on the wing. Note that the allowance margin and the number of wing tip points are related, but not bound, and that two separate input parameters could have been defined for these purposes.

The flap chord input parameter, c_{flap}, must be specified for each panel on wing-1; the values must be consistent with the 2d-geometry variant specified in the *in_2d_aero.txt* aerodynamics tables for the same section. The flap chord is defined based on the projection of the extended flap chord length in the X-Y plane (the horizontal reference plane of the wing or aircraft). More details on defining this parameter are described in Section 6.1.2. If no flaps are specified, the value of the c_{flap} input parameter is set to 1.0.

4.7 Input Files: *in_wing(2x-5x).txt*

A maximum limit of five lifting surfaces, each with a maximum limit of nine spanwise wing section panels is set within MVL-15. In accordance with the *in_wing2x.txt* example shown in Table 13, the user must provide a separate *in_wing*x.txt* file for each lifting surface of the airplane configuration. Typically, one wing comprised of about five spanwise sections and a second wing comprised of about two spanwise sections is sufficient for the analysis of an airplane using MVL-15.

Table 9. File *in_wing1x.txt*: Wing and Lattice Geometry Format

wing Sw geometry input target:			**Sw geo**	1646.8	(ft^2,m^2)		
wing1x Sw aero reference area:			**Swaero**	-1341.7	(ft^2,m^2)		
wing aspect ratio for Sw calc:			**Aratio**	9.413	(non-dim)		
number of spanwise/2 panels:			**npanls**	6	(integer)		
number of chordwise stations:			**jpts-k**	8	(integer)		
number of spanwise/2 stations:			**ipts-k**	80	(integer)		
tip boundary pts min=1 max=20:			**nallow**	2	(integer)		
centerline LE z(+) above grnd:			**zinbrd**	7.000	(ft,m)		
centerline LE x(-) from nose:			**xledge**	-48.000	(ft,m)		
delta Cdrag inputs: All Sref= Sw1 _clean							
segment: clean=0 take=1 appr=2:			**nflght**	1	(integer)		
airplane dCDd0 clean--NO flaps:			**CDdelt**	0.0050	(non-dim)		
airplane dCdtak takeoff--flaps:			**CDflpt**	0.0100	(non-dim)		
airplane dCdapp approach-flaps:			**CDflpa**	0.0000	(non-dim)		
airplane dCDwgr w-landing gear:			**CDgear**	0.0000	(non-dim)		
airplane dCDxsp xtend spoilers:			**CDsplr**	0.0000	(non-dim)		
dihedral (degrees)	LE Sweep (degrees)	0 < 2yi < b (ft,m)	0 < 2yo < b (ft,m)	chord(yi) (ft,m)	chord(yo) (ft,m)	cfratio (cfx/co)	2dratio ($cl\alpha/2\pi\alpha$)
dihed	**sweple**	**ypani**	**ypano**	**cin**	**cout**	**cflap**	**2dratio**
di(n=1)	sw(n=1)	*y(root)*	y1o	*c(root)*	c(y1o)	cfx(n=1)	rat(n=1)
di(n=2)	sw(n=2)	y2i	y2o	c(y2i)	c(y2o)	cfx(n=2)	rat(n=2)
di(n=3)	sw(n=3)	y3i	y3o	c(y3i)	c(y3o)	cfx(n=3)	rat(n=3)
di(n=4)	sw(n=4)	y4i	y4o	c(y4i)	c(y4o)	cfx(n=4)	rat(n=4)
di(n=5)	sw(n=5)	y5i	y5o	c(y5i)	c(y5o)	cfx(n=5)	rat(n=5)
di(n)	sw(n)	yni	*y(b/2)*	c(yni)	*c(b/2)*	cfx(n)	rat(n)

Table 10. File *in_wing1x.txt*: Wing and Lattice Geometry Definitions

Input	Description	2d Scope	3d Scope
Sw geo	wing1 area input, note: Sw(analysis)=Σ(panel areas)	wing 1	wings 1:n
Swaero	output reference areas: Sw/flaps, Sw/o flaps, Swaero	wing 1	wing 1
-Swaero	output reference areas: Sw/flaps, Sw/o flaps	wing 1	wing 1
Aratio	AR input, note: AR(output)= b^2/Sw(analysis)	wing 1	wings 1:n
npanls	number of spanwise(b/2) wing panels, max 2d=1, 3d=9	wing 1	wings 1:n
jpts-k	number of chordwise lattice pts, maximum=41	wing 1	wings 1:n
ipts-k	number of spanwise(b/2) lattice pts, max 2d=3d=100	wing 1	wings 1:n
nallow	allowable number of unconverged points, max=20	wing 1	wings 1:n
zinbrd	wing root LE vertical position	wing 1	wings 1:n
xledge	wing root LE streamwise position	wing 1	wings 1:n
nflght	configuration flag, clean=0 takeoff=1 approach=2	*wing1	wing 1
CDdelt	delta CDo clean configuration, Sref=Swaero	*wing1	wing 1
CDflpt	delta CDt takeoff configuration, Sref=Swaero	*wing1	wing 1
CDflpa	delta CDa approach configuration, Sref=Swaero	*wing1	wing 1
CDgear	delta CDg landing gear increment, Sref=Swaero	*wing1	wing 1
CDsplr	delta CDs spoiler increment, Sref=Swaero	*wing1	wing 1
dihed	wing panel dihedral	wing 1	wings 1:n
sweple	wing panel leading-edge sweep	wing 1	wings 1:n
ypani	wing panel inboard spanwise position (root=0)	wing 1	wings 1:n
ypano	wing panel outboard spanwise position (root=0)	wing 1	wings 1:n
cin	nominal chord length at spanwise location= ypani	wing 1	wings 1:n
cout	nominal chord length at spanwise location= ypano	wing 1	wings 1:n
cflap	wing panel flap chord ratio	wing 1	wings 1:n
2dratio	wing panel lift-curve-slope ratio, cla / $2\pi\alpha$	wing 1	wings 1:n
	* these inputs are for 3d analyses only	-	-

Table 11. File *in_wing1x.txt*: Wing and Lattice Geometry Airfoil Example

" wing Sw geometry input target:	**Sw geo "**	1000.0
wing1x Sw aero reference area:	**Swaero "**	1000.0
" wing aspect ratio for Sw calc:	**Aratio "**	1000.0
" number of spanwise/2 panels:	**npanls "**	1
" number of chordwise stations:	**jpts-k "**	41
" number of spanwise/2 stations:	**ipts-k "**	20
" tip boundary pts min=1 max=20:	**nallow "**	0
" centerline LE z(+) above grnd:	**zinbrd "**	0.000
" centerline LE x(-) from nose:	**xledge "**	-20.000
"----------"		
" delta Cdrag inputs: All Sref= Sw1 _clean "		
"----------"		
" segment: clean=0 take=1 appr=2:	**nflght "**	0
" airplane dCDd0 clean--NO flaps:	**CDdelt "**	0.0000
" airplane dCdtak takeoff--flaps:	**CDflpt "**	0.0000
" airplane dCdapp approach-flaps:	**CDflpa "**	0.0000
" airplane dCDwgr w-landing gear:	**CDgear "**	0.0000
" airplane dCDxsp xtend spoilers:	**CDsplr "**	0.0000
"----------"		

"dihed	**sweple**	**ypani**	**ypano**	**cin**	**cout**	**cflap**	**2dratio**
0.0000	0.0000	0.0000	500.0	1.000	1.000	1.000	1.000

Table 12. File *in_wing1x.txt*: Wing and Lattice Geometry Wing 1 Example

" wing Sw geometry input target:	**Sw geo "**	1646.8
" wing1 Sw aero reference area:	**Swaero "**	-1341.7
" wing aspect ratio for Sw calc:	**Aratio "**	9.413
" number of spanwise/2 panels:	**npanls "**	6
" number of chordwise stations:	**jpts-k "**	8
" number of spanwise/2 stations:	**ipts-k "**	80
" tip boundary pts min=1 max=20:	**nallow "**	2
" centerline LE z(+) above grnd:	**zinbrd "**	7.000
" centerline LE x(-) from nose:	**xledge "**	-48.000
"----------"		
" delta Cdrag inputs: All Sref= Sw1 _clean "		
"----------"		
" segment: clean=0 take=1 appr=2:	**nflght "**	1
" airplane dCDd0 clean--NO flaps:	**CDdelt "**	0.0050
" airplane dCdtak takeoff--flaps:	**CDflpt "**	0.0100
" airplane dCdapp approach-flaps:	**CDflpa "**	0.0000
" airplane dCDwgr w-landing gear:	**CDgear "**	0.0000
" airplane dCDxsp xtend spoilers:	**CDsplr "**	0.0000
"----------"		

"dihed	**sweple**	**ypani**	**ypano**	**cin**	**cout**	**cflap**	**2dratio**
0.000	0.0000	0.0000	6.000	21.700	21.700	1.0327	1.000
6.000	28.118	6.0000	16.000	21.700	18.400	1.0327	1.000
6.000	28.118	16.0000	34.000	18.400	12.459	1.0528	1.000
6.000	28.118	34.0000	47.000	12.459	8.168	1.0528	1.000
6.000	28.118	47.0000	55.017	8.168	5.523	1.0000	1.000
6.000	49.824	55.0167	62.250	5.523	1.425	1.0000	1.000

Table 13. File *in_wing2x-5x.txt*: Wing and Lattice Geometry, Wing 2 Example

" wing Sw geometry input target:	**Sw geo "**	381.0
*		*
" wing aspect ratio for Sw calc:	**Aratio "**	5.554
" number of spanwise/2 panels:	**npanls "**	2
" number of chordwise stations:	**jpts-k "**	4
" number of spanwise/2 stations:	**ipts-k "**	40
" tip boundary pts min=1 max=20:	**nallow "**	2
" centerline LE z(+) above grnd:	**zinbrd "**	13.333
" centerline LE x(-) from nose:	**xledge "**	-104.5
"----------"		
*		
"----------"		
*		*
*		*
*		*
*		*
*		*
*		*
"----------"		

"dihed	sweple	ypani	ypano	cin	cout	cflap	2dratio
0.000	0.000	0.000	3.000	11.000	11.000	1.000	1.000
10.000	34.500	3.000	23.000	11.000	4.750	1.000	1.000

5.0 Output File Examples, Definitions, and Formats

Section 5 provides information about the general format, parameter definitions, and typical parameter values associated with each of the MVL-15 *output.txt* files. Section 5 also provides example output files from 2d- and 3d- analyses, modified only to the extent required for presentation in this report. The following sections describe the content of these output files in more detail.

5.1 Output File: *out_aero.txt*

The general format, parameter definitions, and typical parameter values of the *out_aero.txt* file are shown in Table 14. Example output files resulting from airfoil and wing analyses are provided in Table 15 and Table 16, respectively. The integrated aerodynamic results, including wing areas, reference areas, lift coefficients, and drag coefficient components are tabulated in the *out_aero.txt* file. Results for each wing and for the multi-wing configuration are listed separately by row and are grouped for each specified angle of attack. For example, consider a configuration with a wing and a horizontal stabilizer analyzed at multiple angles of attack. After the analysis at the first angle of attack is complete, individual aerodynamic results are listed for the main wing (*row-1*) and the horizontal stabilizer (*row-2*); then, combined aerodynamic results are listed in *row-3* and *row-4.* Similar output lists are generated until the analysis at the final angle of attack is complete.

The results listed in *row-3* are based on the wing-1 reference area with flaps extended (the geometry is specified by setting the c_{flap} input parameter (file: *in_wing1x.txt*) to a value greater than 1.0), and the results listed in *row-4* are based on the wing-1 reference area with flaps retracted. The results listed in *row-3* and *row-4* will be identical if the use of flaps is not specified. The wing areas, and the reference areas of *row-3* and *row-4*, are calculated internally by summing the projected areas of each wing panel. As described in Section 4.6, the *Swaero* input parameter (file: *in_wing1x.txt*) can be specified as either a positive or negative number, depending on whether the user intends to modify the *out_aero.txt* output with a fifth row of data at each angle of attack. If the input value is negative, the *row-5* output will not be added. If the input value is positive, the difference of the *Swaero* and the *Swgeo* input parameters (file: *in_wing1x.txt*) is calculated. If the absolute value of the difference is greater than 10, the *row-5* output will be added.

The output reference areas with flaps retracted and extended are accessed and utilized as default reference areas by the MVL-15 *3d-Results Presentation Utility* when generating airplane lift curves and drag polars. Note that the *Swaero* input value is accessed and saved by the utility file, but modifying the results to reflect the *Swaero* reference area requires a simple, but manual, modification of the results table. If the *Swaero* input value is a negative number, *row-5* will not be generated; however, the *Swaero* input value is accessed and saved for manual modifications within the MVL-15 *3d-Results Presentation Utility* file.

Table 14. File *out_aero.txt*: Integrated Aerodynamics Output Definitions

Output	Description
17	number of output angles *(n=nalpha, "in_alphas.txt")*
07	spanwise output index *(n=n(alfput), "in_alphas.txt")*
01...	aero output index=1 *(n=1, "in_alphas.txt")*
wing 1	wing 1 aerodynamics, Sref: wing 1 area, with flaps
wing 2	wing 2 aerodynamics, Sref: wing 2 area
S1 flap	combined aerodynamics, Sref: wing 1 area, with flaps
S1 nofl	combined aerodynamics, Sref: wing 1 area, no flaps
S_wing	wing area, projected to horizontal plane
Gm/Sk | AR	wing circulation
Gm/Sk **| AR**	wing Aspect Ratio
alpdeg	wing angle of attack
CL wtd	section alpha-zero-lift (cl=0)
CL avg	effective angle of attack for viscous table look-up
CLstal	spanwise d(alpha) due to d(circulation, gamma)
CD-ind	section lift curve slope at angle(spani) = alchrt
cdf-2d	lift-curve-slope augmentation factor
dCDo-3D	intermediate factor related to cdi, ai/cf * slopl
dCDflps	dimensional flap chord, f(2y/b)
dCDgear	spanwise (b/2) circulation (gamma)
dCDsplr	spanwise (b/2) lift coefficient
CD-tot	spanwise (b/2) lift coefficient * chord
...17	aero output index=n *(n=nalpha, "in_alphas.txt")*
cbar1	average chord of wing 1, =S1 flap / span
toler1	initial convergence tolerance, delta cl(y)
tolern	final (nloops) convergence tolerance, delta cl(y), *3d only*
azlist	listed 2d alpha-zero-lift (cl=0), *2d only*
fstcvg	iteration convergence factor, step to step fraction
nallow	number of allowable unconverged spanwise stations
nloops	total number of interation loops
Sw aero	post-analysis reference area, *3d only*
2d azl	MVL15 2d Result: alpha(cl=0), *2d only*
description	*2d airfoil description or filename, 2d only*

Table 15. File *out_aero.txt*: Integrated Aerodynamics, Airfoil Example

	S_flap	Gm/Sk AR	alpdeg	CL wtd	CL avg	CLstal	CD-ind	cdf-2d	dCDo-3D	dCDflps	dCDgear	dCDsplr	CD-tot
wing 1	1000.0	0.3206	0.000	0.3206	0.3206	0.3206	0.000	0.0113	0.000	0.000	0.000	0.000	0.0113
wing 2	0.0	0.0000	0.000	0.0000	0.0000	0.0000	0.000	0.0000	0.000	0.000	0.000	0.000	0.0000
S1 flap	1000.0	1000.0	0.000	0.3206	0.3206	0.3206	0.000	0.0113	0.000	0.000	0.000	0.000	0.0113
S1 nofl	1000.0	1000.0	0.000	0.3206	0.3206	0.3206	0.000	0.0113	0.000	0.000	0.000	0.000	0.0113

cbar1	1.0000
toler1	0.0005
azlist	-2.9232
fstcvg	0.7000
nallow	0
nloops	2
2d azl	-2.9232

p1dsi_LE_0df_pt0cfr_1pt0cfx_0ds_valid_2015

Table 16. File *out_aero.txt*: Integrated Aerodynamics, Wing Example

17													
07		**Gm/Sk**											
01	**S_flap**	**AR**	**alpdeg**	**CL wtd**	**CL avg**	**CLstal**	**CD-ind**	**cdf-2d**	**dCDo-3D**	**dCDflps**	**dCDgear**	**dCDsplr**	**CD-tot**
wing 1	1709.4	885.39	0.000	0.518	0.508	0.508	0.001	0.0515	0.000	0.000	0.000	0.000	0.0529
wing 2	381.0	48.343	-0.300	0.127	0.124	0.124	0.003	0.0092	0.000	0.000	0.000	0.000	0.0122
S1 flap	1709.4	9.067	0.000	0.546	0.536	0.546	0.002	0.0535	0.005	0.010	0.000	0.000	0.0701
S1 nofl	1645.1	9.422	0.000	0.568	0.557	0.568	0.002	0.0556	0.005	0.010	0.000	0.000	0.0728
etc...		**Gm/Sk**											
07	**S_flap**	**AR**	**alpdeg**	**CL wtd**	**CL avg**	**CLstal**	**CD-ind**	**cdf-2d**	**dCDo-3D**	**dCDflps**	**dCDgear**	**dCDsplr**	**CD-tot**
wing 1	1709.4	1917.17	6.000	1.122	1.109	1.109	0.029	0.0426	0.000	0.000	0.000	0.000	0.0712
wing 2	381.0	31.292	0.400	0.082	0.079	0.079	0.004	0.0099	0.000	0.000	0.000	0.000	0.0135
S1 flap	1709.4	9.067	6.000	1.140	1.127	1.140	0.029	0.0448	0.005	0.010	0.000	0.000	0.0886
S1 nofl	1645.1	9.422	6.000	1.184	1.171	1.184	0.031	0.0466	0.005	0.010	0.000	0.000	0.0921
etc...		**Gm/Sk**											
17	**S_flap**	**AR**	**alpdeg**	**CL wtd**	**CL avg**	**CLstal**	**CD-ind**	**cdf-2d**	**dCDo-3D**	**dCDflps**	**dCDgear**	**dCDsplr**	**CD-tot**
wing 1	1709.4	3268.92	15.000	1.912	1.867	1.867	0.122	0.0556	0.000	0.000	0.000	0.000	0.1775
wing 2	381.0	21.938	1.600	0.058	0.056	0.056	0.004	0.0103	0.000	0.000	0.000	0.000	0.0143
S1 flap	1709.4	9.067	15.000	1.925	1.880	1.925	0.123	0.0579	0.005	0.010	0.000	0.000	0.1951
S1 nofl	1645.1	9.422	15.000	2.000	1.953	2.000	0.128	0.0601	0.005	0.010	0.000	0.000	0.2027
cbar1	13.7305												
toler1	0.0001												
tolern	0.0001												
fstcvg	0.7000												
nallow	2												
nloops	8												
Swaero	1341.7												

5.2 Output File: *out_span.txt*

The general format, parameter definitions, and typical parameter values of the *out_span.txt* file are shown in Table 17. Example output files resulting from both airfoil and wing analyses are provided in Table 18 and Table 19, respectively. The spanwise output file provides aerodynamic data (summed in the chordwise direction) at each spanwise station of the wing. The spanwise lift distribution and accompanying charts are automatically generated from this data by the MVL-15 *3d-Results Presentation Utility* file at an angle of attack based on the specified value of the input parameter, *alfput* (file: *in_alphas.txt*).

Table 17. File *out_span.txt*: Spanwise Aerodynamics Output Definitions

Output	Description
spani	wing spanwise (b/2) index, i
alpha	wing angle of attack
ai/cf	induced angle of attack (c reference=cf)
alpzl	section alpha (cl=0)
alchrt	effective angle of attack for viscous table look-up
daldgy	spanwise d(alpha) due to d(circulation, gamma)
slopl	section lift curve slope at angle(spani) = alchrt
clarati	lift-curve-slope augmentation factor
dclai	intermediate factor related to cdi, ai/cf * slopl
cflapy	dimensional flap chord, f(2y/b)
gamofy	spanwise (b/2) circulation (gamma)
clofy	spanwise (b/2) lift coefficient
ccldy	spanwise (b/2) lift coefficient * chord
staly	clofy, including stall penalty factor (in_2d_aero input)
cfraty	spanwise (b/2) flap chord ratio, cflap/co
cdpry	spanwise (b/2) section drag at angle(spani) = alchrt
cdindy	spanwise (b/2) induced drag
cdtoty	spanwise (b/2) total drag

Table 18. File *out_span.txt*: Spanwise Aerodynamics, Airfoil Example

wing 1

spani	alpha	ai/cf	alpzl	alchrt	daldgy	slopl	clarati	dclai	cflapy	gamofy	clofy	ccldy	stcly	cfraty	cdpry	cdindy	cdtoty
1	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
2	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
3	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
4	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
5	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
6	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
7	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
8	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
9	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
10	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
11	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
12	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
13	0.0	0.000	-2.923	0.000	0.000	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
14	0.0	0.000	-2.923	0.000	0.001	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
15	0.0	0.000	-2.923	0.000	0.001	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
16	0.0	0.000	-2.923	0.000	0.001	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
17	0.0	0.000	-2.923	0.000	0.002	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
18	0.0	0.000	-2.923	0.000	0.003	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
19	0.0	0.000	-2.923	0.000	0.083	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113
20	0.0	0.000	-2.923	0.000	0.287	0.1097	1.000	0.000	1.000	0.160	0.321	0.321	0.000	1.000	0.0113	0.0000	0.0113

Table 19. File *out_span.txt*: Spanwise Aerodynamics, Wing Example

wing 1																
spani	**alpha**	**ai/cf**	**alpzl**	**alchrt**	**daldgy**	**slopl**	**slrati**	**dslai**	**cflapy**	**gamofy**	**clofy**	**ccldy**	**staly**	**cfraty**	**cdpry**	**cdindy**	**cdtoty**
1	6.0	-2.305	-3.472	3.695	0.000	0.1279	1.1660	0.2947	22.410	10.268	0.916	20.537	0.916	1.0327	0.0413	0.0369	0.0782
2	6.0	-2.305	-3.472	3.695	0.000	0.1279	1.1660	0.2948	22.410	10.268	0.916	20.536	0.916	1.0327	0.0413	0.0369	0.0782
3	6.0	-2.306	-3.472	3.695	0.000	0.1279	1.1660	0.2948	22.410	10.267	0.916	20.535	0.916	1.0327	0.0413	0.0369	0.0782
4	6.0	-2.306	-3.472	3.694	-0.001	0.1279	1.1660	0.2949	22.410	10.267	0.916	20.533	0.916	1.0327	0.0413	0.0369	0.0782
5	6.0	-2.307	-3.472	3.693	-0.001	0.1279	1.1660	0.2950	22.410	10.265	0.916	20.531	0.916	1.0327	0.0413	0.0369	0.0782
6	6.0	-2.308	-3.472	3.692	-0.001	0.1279	1.1660	0.2951	22.410	10.264	0.916	20.529	0.916	1.0327	0.0413	0.0369	0.0782
7	6.0	-2.308	-3.472	3.692	-0.001	0.1279	1.1660	0.2951	22.410	10.264	0.916	20.527	0.916	1.0327	0.0413	0.0369	0.0782
8	6.0	-2.308	-3.472	3.692	0.000	0.1279	1.1660	0.2952	22.410	10.263	0.916	20.527	0.916	1.0327	0.0413	0.0369	0.0782
9	6.0	-2.287	-3.472	3.713	0.021	0.1279	1.1660	0.2925	22.239	10.215	0.919	20.430	0.919	1.0327	0.0413	0.0367	0.0780
10	6.0	-2.251	-3.472	3.749	0.037	0.1279	1.1660	0.2878	21.935	10.127	0.923	20.253	0.923	1.0327	0.0413	0.0363	0.0776
11	6.0	-2.217	-3.472	3.783	0.034	0.1279	1.1660	0.2835	21.670	10.051	0.928	20.102	0.928	1.0327	0.0412	0.0359	0.0771
12	6.0	-2.182	-3.472	3.818	0.035	0.1279	1.1660	0.2790	21.405	9.976	0.932	19.952	0.932	1.0327	0.0412	0.0355	0.0767
13	6.0	-2.146	-3.472	3.854	0.036	0.1279	1.1661	0.2744	21.140	9.901	0.937	19.802	0.937	1.0327	0.0412	0.0351	0.0763
14	6.0	-2.108	-3.472	3.892	0.038	0.1279	1.1661	0.2696	20.874	9.827	0.942	19.654	0.942	1.0327	0.0411	0.0347	0.0758
15	6.0	-2.069	-3.472	3.931	0.039	0.1279	1.1661	0.2646	20.609	9.754	0.947	19.507	0.947	1.0327	0.0411	0.0342	0.0753
16	6.0	-2.029	-3.472	3.971	0.041	0.1279	1.1661	0.2594	20.344	9.681	0.952	19.362	0.952	1.0327	0.0410	0.0337	0.0747
17	6.0	-1.986	-3.472	4.014	0.043	0.1279	1.1661	0.2540	20.079	9.610	0.957	19.219	0.957	1.0327	0.0410	0.0332	0.0742
18	6.0	-1.941	-3.472	4.059	0.045	0.1279	1.1661	0.2482	19.813	9.540	0.963	19.079	0.963	1.0327	0.0409	0.0326	0.0736
19	6.0	-1.893	-3.472	4.107	0.048	0.1279	1.1661	0.2421	19.548	9.472	0.969	18.944	0.969	1.0327	0.0409	0.0320	0.0729
20	6.0	-1.841	-3.472	4.159	0.052	0.1279	1.1661	0.2354	19.283	9.408	0.976	18.815	0.976	1.0327	0.0408	0.0314	0.0722
etc...																	
77	6.0	-0.385	-2.923	5.615	-0.176	0.1015	0.9254	0.0391	2.968	1.286	0.867	2.572	0.867	1.0000	0.0062	0.0058	0.0120
78	6.0	-0.937	-2.923	5.063	-0.551	0.1015	0.9254	0.0950	2.527	1.024	0.811	2.048	0.811	1.0000	0.0060	0.0133	0.0192
79	6.0	-1.952	-2.923	4.048	-1.015	0.1015	0.9254	0.1981	2.086	0.738	0.708	1.476	0.708	1.0000	0.0056	0.0241	0.0297
80	6.0	-3.695	-2.923	2.305	-1.743	0.1015	0.9254	0.3749	1.645	0.437	0.531	0.873	0.531	1.0000	0.0055	0.0342	0.0397
wing 2																	
81	0.4	-2.371	-2.923	-1.971	0.000	0.1015	0.9255	0.2407	11.000	0.531	0.097	1.063	0.097	1.0000	0.0097	0.0040	0.0137
82	0.4	-2.371	-2.923	-1.971	0.001	0.1015	0.9255	0.2406	11.000	0.532	0.097	1.063	0.097	1.0000	0.0097	0.0040	0.0137
etc...																	
120	0.4	-2.877	-2.923	-2.477	-0.149	0.1015	0.9255	0.2920	4.840	0.110	0.045	0.219	0.045	1.0000	0.0105	0.0023	0.0128

5.3 Output File: *out_geom.txt*

The general format, parameter definitions, and typical parameter values of the *out_geom.txt* file are shown in Table 20. Example output files resulting from both airfoil and wing analyses are provided in Table 21 and Table 22, respectively. For 2d-analyses, the geometry results are output at an angle of attack of zero degrees; for 3d-analyses, the geometry results are output at the angle of attack specified by the input parameter, *alfput* (file: *in_alphas.txt*). Section 7 will describe how the MVL-15 *3d-Results Presentation Utility* file can be used to automatically create charts for visualizing the tabulated analysis geometry results.

Table 20. File *out_geom.txt*: Geometry Output Definitions

Output	Description
panel	wing panel index, n *(inpan)*
i-span	spanwise (b/2) lattice index, *(i)*
j-chrd	chordwise lattice index, *(j)*
k-wing	wing index, *(k)*
aleff	effective angle of attack, 2d=a-azl, 3d=a-ai
xc	control point x-coordinate
yc	control point y-coordinate
zc	control point z-coordinate
xvi	inboard vortex x-coordinate
yrvi	right-side wing inboard vortex y-coordinate
ylvi	left-side wing inboard vortex y-coordinate
zvi	inboard vortex z-coordinate
xvo	outboard vortex x-coordinate
yrvo	right-side wing outboard vortex y-coordinate
ylvo	left-side wing outboard vortex y-coordinate
zvo	outboard vortex z-coordinate
xite	inboard vortex x-coordinate at trailing edge
zite	inboard vortex z-coordinate at trailing edge
xote	outboard vortex x-coordinate at trailing edge
zote	outboard vortex z-coordinate at trailing edge
cpang	control point resultant incidence angle
viang	inboard vortex resultant incidence angle
voang	outboard vortex resultant incidence angle

Table 21. File *out_geom.txt*: Geometry, Airfoil Example

panel	span-i	j-chrd	k-wing	aleff	xc	yc	zc	xvi	yrvi	ylvi	zvi	xvo	yrvo	ylvo	zvo	xite	zite	xote	zote	cpang	viang	voang
1	1	1	1	-2.92	-20.02	12.5	0.00	-20.01	0.0	0.0	0.00	-20.01	25.0	-25.0	0.00	-21.00	0.00	-21.00	0.00	-4.64	-4.64	-4.64
1	1	2	1	-2.92	-20.04	12.5	0.00	-20.03	0.0	0.0	0.00	-20.03	25.0	-25.0	0.00	-21.00	0.00	-21.00	0.00	-4.29	-4.29	-4.29
1	1	3	1	-2.92	-20.07	12.5	0.00	-20.05	0.0	0.0	0.00	-20.05	25.0	-25.0	0.00	-21.00	0.00	-21.00	0.00	-3.94	-3.94	-3.94
1	1	**etc.**	1																			
1	1	39	1	-2.92	-20.95	12.5	-0.01	-20.93	0.0	0.0	-0.01	-20.93	25.0	-25.0	-0.01	-21.00	-0.01	-21.00	-0.01	4.31	4.31	4.31
1	1	40	1	-2.92	-20.97	12.5	-0.02	-20.96	0.0	0.0	-0.02	-20.96	25.0	-25.0	-0.02	-21.00	-0.02	-21.00	-0.02	4.47	4.47	4.47
1	1	41	1	-2.92	-20.99	12.5	-0.02	-20.98	0.0	0.0	-0.02	-20.98	25.0	-25.0	-0.02	-21.00	-0.02	-21.00	-0.02	4.62	4.62	4.62
1	2	1	1	-2.92	-20.02	37.5	0.00	-20.01	25.0	-25.0	0.00	-20.01	50.0	-50.0	0.00	-21.00	0.00	-21.00	0.00	-4.64	-4.64	-4.64
1	2	2	1	-2.92	-20.04	37.5	0.00	-20.03	25.0	-25.0	0.00	-20.03	50.0	-50.0	0.00	-21.00	0.00	-21.00	0.00	-4.29	-4.29	-4.29
1	2	3	1	-2.92	-20.07	37.5	0.00	-20.05	25.0	-25.0	0.00	-20.05	50.0	-50.0	0.00	-21.00	0.00	-21.00	0.00	-3.94	-3.94	-3.94
1	2	**etc.**	1																			
1	2	39	1	-2.92	-20.95	37.5	-0.01	-20.93	25.0	-25.0	-0.01	-20.93	50.0	-50.0	-0.01	-21.00	-0.01	-21.00	-0.01	4.31	4.31	4.31
1	2	40	1	-2.92	-20.97	37.5	-0.02	-20.96	25.0	-25.0	-0.02	-20.96	50.0	-50.0	-0.02	-21.00	-0.02	-21.00	-0.02	4.47	4.47	4.47
1	2	41	1	-2.92	-20.99	37.5	-0.02	-20.98	25.0	-25.0	-0.02	-20.98	50.0	-50.0	-0.02	-21.00	-0.02	-21.00	-0.02	4.62	4.62	4.62
	etc.																					
1	20	1	1	-2.92	-20.02	487.5	0.00	-20.01	475.0	-475.0	0.00	-20.01	500.0	-500.0	0.00	-21.00	0.00	-21.00	0.00	-4.64	-4.64	-4.64
1	20	2	1	-2.92	-20.04	487.5	0.00	-20.03	475.0	-475.0	0.00	-20.03	500.0	-500.0	0.00	-21.00	0.00	-21.00	0.00	-4.29	-4.29	-4.29
1	20	3	1	-2.92	-20.07	487.5	0.00	-20.05	475.0	-475.0	0.00	-20.05	500.0	-500.0	0.00	-21.00	0.00	-21.00	0.00	-3.94	-3.94	-3.94
1	20	**etc.**	1																			
1	20	39	1	-2.92	-20.95	487.5	-0.01	-20.93	475.0	-475.0	-0.01	-20.93	500.0	-500.0	-0.01	-21.00	-0.01	-21.00	-0.01	4.31	4.31	4.31
1	20	40	1	-2.92	-20.97	487.5	-0.02	-20.96	475.0	-475.0	-0.02	-20.96	500.0	-500.0	-0.02	-21.00	-0.02	-21.00	-0.02	4.47	4.47	4.47
1	20	41	1	-2.92	-20.99	487.5	-0.02	-20.98	475.0	-475.0	-0.02	-20.98	500.0	-500.0	-0.02	-21.00	-0.02	-21.00	-0.02	4.62	4.62	4.62

Table 22. File *out_geom.txt*: Geometry, Wing Example

panel	i-span	j-chrd	k-wing	aleff	xc	yc	zc	xvi	yrvi	ylvi	zvi	xvo	yrvo	ylvo	zvo	xite	zite	xote	zote	cpang	viang	voang
1	1	1	1	3.70	-50.09	0.39	6.78	-48.70	0.00	0.00	6.93	-48.70	0.78	-0.78	6.93	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	1	2	1	3.70	-52.88	0.39	6.49	-51.48	0.00	0.00	6.63	-51.48	0.78	-0.78	6.63	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	1	3	1	3.70	-55.66	0.39	6.19	-54.27	0.00	0.00	6.34	-54.27	0.78	-0.78	6.34	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	1	**etc.**	1																			
1	1	8	1	3.70	-69.59	0.39	4.73	-68.20	0.00	0.00	4.88	-68.20	0.78	-0.78	4.88	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	2	1	1	3.69	-50.09	1.17	6.78	-48.70	0.78	-0.78	6.93	-48.70	1.56	-1.56	6.93	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	2	2	1	3.69	-52.88	1.17	6.49	-51.48	0.78	-0.78	6.63	-51.48	1.56	-1.56	6.63	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	2	3	1	3.69	-55.66	1.17	6.19	-54.27	0.78	-0.78	6.34	-54.27	1.56	-1.56	6.34	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
1	2	**etc.**	1																			
1	2	8	1	3.69	-69.59	1.17	4.73	-68.20	0.78	-0.78	4.88	-68.20	1.56	-1.56	4.88	-70.29	4.66	-70.29	4.66	8.47	9.47	9.47
	etc.																					
2	9	1	1	3.71	-50.40	6.61	6.81	-48.82	6.23	-6.23	6.94	-49.22	7.00	-7.00	6.98	-70.41	4.67	-70.48	4.74	9.47	9.47	9.47
2	9	2	1	3.71	-53.16	6.61	6.52	-51.60	6.23	-6.23	6.65	-51.96	7.00	-7.00	6.69	-70.41	4.67	-70.48	4.74	9.47	9.47	9.47
2	9	3	1	3.71	-55.93	6.61	6.23	-54.39	6.23	-6.23	6.35	-54.71	7.00	-7.00	6.40	-70.41	4.67	-70.48	4.74	9.47	9.47	9.47
2	9	**etc.**	1																			
2	9	8	1	3.71	-69.75	6.61	4.78	-68.32	6.23	-6.23	4.89	-68.42	7.00	-7.00	4.96	-70.41	4.67	-70.48	4.74	9.47	9.47	9.47
etc.	**etc.**																					
6	80	1	1	2.31	-82.41	61.86	9.27	-81.85	61.47	-61.47	9.29	-82.76	62.25	-62.25	9.27	-83.65	9.10	-84.13	9.13	9.47	8.92	8.92
6	80	2	1	2.31	-82.61	61.86	9.25	-82.09	61.47	-61.47	9.26	-82.93	62.25	-62.25	9.26	-83.65	9.10	-84.13	9.13	9.47	8.92	8.92
6	80	3	1	2.31	-82.82	61.86	9.23	-82.32	61.47	-61.47	9.24	-83.11	62.25	-62.25	9.24	-83.65	9.10	-84.13	9.13	9.47	8.92	8.92
5	80	**etc.**	1																			
6	80	8	1	2.31	-83.84	61.86	9.12	-83.48	61.47	-61.47	9.12	-84.00	62.25	-62.25	9.14	-83.65	9.10	-84.13	9.13	9.47	8.92	8.92
1	1	1	2	-1.97	-106.6	0.29	13.32	-105.2	0.00	0.00	13.33	-105.2	0.58	-0.58	13.33	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	1	2	2	-1.97	-109.3	0.29	13.30	-107.9	0.00	0.00	13.31	-107.9	0.58	-0.58	13.31	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	1	3	2	-1.97	-112.1	0.29	13.28	-110.7	0.00	0.00	13.29	-110.7	0.58	-0.58	13.29	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	1	4	2	-1.97	-114.8	0.29	13.26	-113.4	0.00	0.00	13.27	-113.4	0.58	-0.58	13.27	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	2	1	2	-1.97	-106.6	0.86	13.32	-105.2	0.58	-0.58	13.33	-105.2	1.15	-1.15	13.33	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	2	2	2	-1.97	-109.3	0.86	13.30	-107.9	0.58	-0.58	13.31	-107.9	1.15	-1.15	13.31	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	2	3	2	-1.97	-112.1	0.86	13.28	-110.7	0.58	-0.58	13.29	-110.7	1.15	-1.15	13.29	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
1	2	4	2	-1.97	-114.8	0.86	13.26	-113.4	0.58	-0.58	13.27	-113.4	1.15	-1.15	13.27	-115.5	13.26	-115.5	13.26	3.12	3.32	3.32
	etc.																					
2	40	1	2	-2.48	-119.0	22.71	16.71	-118.2	22.43	-22.43	16.66	-118.5	23.00	-23.00	16.76	-122.8	16.63	-123.0	16.73	3.32	3.32	3.32
2	40	2	2	-2.48	-120.2	22.71	16.70	-119.4	22.43	-22.43	16.65	-119.7	23.00	-23.00	16.75	-122.8	16.63	-123.0	16.73	3.32	3.32	3.32
2	40	3	2	-2.48	-121.4	22.71	16.69	-120.6	22.43	-22.43	16.65	-120.9	23.00	-23.00	16.74	-122.8	16.63	-123.0	16.73	3.32	3.32	3.32
2	40	4	2	-2.48	-122.6	22.71	16.68	-121.9	22.43	-22.43	16.64	-122.1	23.00	-23.00	16.74	-122.8	16.63	-123.0	16.73	3.32	3.32	3.32

5.4 Output File: *out_xzang.txt*

The general format, parameter definitions, and typical parameter values of the *out_xzang.txt* file are shown in Table 23. Example output files resulting from airfoil and wing analyses are provided in Table 24 and Table 25, respectively. This file is a subset of the *out_geom.txt* file, and was generated primarily to simplify in-depth reviews of certain geometry output values.

5.5 Output File: *out_diag.txt*

Examples of the *out_diag.txt* file are not provided. The file replicates all information written to the screen during MVL-15 execution, provides diagnostic convergence and iteration information, and echoes the values of selected input parameters.

Table 23. File *out_xzang.txt*: Geometry Subset Output Definitions

Output	Description
panel	wing panel index, n *(inpan)*
i-span	spanwise (b/2) lattice index, *(i)*
j-chrd	chordwise lattice index, *(j)*
k-wing	wing index, *(k)*
aleff	effective angle of attack, 2d=a-azl, 3d=a-ai
xc	control point x-coordinate
zc	control point z-coordinate
cpang	control point resultant angle
camang	control point incidence angle
viang	inboard vortex resultant angle
camangi	inboard vortex incidence angle
voang	outboard vortex resultant angle
camango	outboard vortex incidence angle

Table 24. File *out_xzang.txt*: Geometry Subset, Airfoil Example

panel	i-span	j-chrd	k-wing	aleff	xc	zc	cpang	camang	viang	camangi	voang	camango
1	1	1	1	-2.923	-20.02	0.00	-4.642	-4.467	-4.642	-4.642	-4.642	-4.642
1	1	2	1	-2.923	-20.04	0.00	-4.292	-4.118	-4.292	-4.292	-4.292	-4.292
1	1	3	1	-2.923	-20.07	0.00	-3.943	-3.768	-3.943	-3.943	-3.943	-3.943
1	1	**etc...**	1									
1	1	39	1	-2.923	-20.95	-0.01	4.313	4.391	4.313	4.313	4.313	4.313
1	1	40	1	-2.923	-20.97	-0.02	4.469	4.546	4.469	4.469	4.469	4.469
1	1	41	1	-2.923	-20.99	-0.02	4.624	4.701	4.624	4.624	4.624	4.624
1	2	1	1	-2.923	-20.02	0.00	-4.642	-4.467	-4.642	-4.642	-4.642	-4.642
1	2	2	1	-2.923	-20.04	0.00	-4.292	-4.118	-4.292	-4.292	-4.292	-4.292
1	2	3	1	-2.923	-20.07	0.00	-3.943	-3.768	-3.943	-3.943	-3.943	-3.943
1	2	**etc...**	1									
1	2	39	1	-2.923	-20.95	-0.01	4.313	4.391	4.313	4.313	4.313	4.313
1	2	40	1	-2.923	-20.97	-0.02	4.469	4.546	4.469	4.469	4.469	4.469
1	2	41	1	-2.923	-20.99	-0.02	4.624	4.701	4.624	4.624	4.624	4.624
1	20	1	1	-2.923	-20.02	0.00	-4.642	-4.467	-4.642	-4.642	-4.642	-4.642
1	20	2	1	-2.923	-20.04	0.00	-4.292	-4.118	-4.292	-4.292	-4.292	-4.292
1	20	3	1	-2.923	-20.07	0.00	-3.943	-3.768	-3.943	-3.943	-3.943	-3.943
1	20	**etc...**	1									
1	20	39	1	-2.923	-20.95	-0.01	4.313	4.391	4.313	4.313	4.313	4.313
1	20	40	1	-2.923	-20.97	-0.02	4.469	4.546	4.469	4.469	4.469	4.469
1	20	41	1	-2.923	-20.99	-0.02	4.624	4.701	4.624	4.624	4.624	4.624

Table 25. File *out_xzang.txt*: Geometry Subset, Wing Example

panel	i-span	j-chrd	k-wing	aleff	xc	zc	cpang	camang	viang	camangi	voang	camango
1	1	1	1	3.695	-50.089	6.780	8.472	0.000	9.472	0.000	9.472	0.000
1	1	2	1	3.695	-52.875	6.488	8.472	0.000	9.472	0.000	9.472	0.000
1	1	3	1	3.695	-55.661	6.195	8.472	0.000	9.472	0.000	9.472	0.000
1	1	**etc.**	1									
1	1	8	1	3.695	-69.590	4.731	8.472	0.000	9.472	0.000	9.472	0.000
1	2	1	1	3.695	-50.089	6.780	8.472	0.000	9.472	0.000	9.472	0.000
1	2	2	1	3.695	-52.875	6.488	8.472	0.000	9.472	0.000	9.472	0.000
1	2	3	1	3.695	-55.661	6.195	8.472	0.000	9.472	0.000	9.472	0.000
1	2	**etc.**	1									
1	2	8	1	3.695	-69.590	4.731	8.472	0.000	9.472	0.000	9.472	0.000
	etc.											
2	9	1	1	3.713	-50.400	6.812	9.472	0.000	9.472	0.000	9.472	0.000
2	9	2	1	3.713	-53.164	6.522	9.472	0.000	9.472	0.000	9.472	0.000
2	9	3	1	3.713	-55.929	6.231	9.472	0.000	9.472	0.000	9.472	0.000
2	9	**etc.**	1									
2	9	8	1	3.713	-69.752	4.778	9.472	0.000	9.472	0.000	9.472	0.000
etc.	**etc.**											
6	80	1	1	2.305	-82.407	9.270	9.472	0.000	8.923	0.000	8.923	0.000
6	80	2	1	2.305	-82.612	9.248	9.472	0.000	8.923	0.000	8.923	0.000
6	80	3	1	2.305	-82.816	9.227	9.472	0.000	8.923	0.000	8.923	0.000
6	80	**etc.**	1									
6	80	8	1	2.305	-83.839	9.119	9.472	0.000	8.923	0.000	8.923	0.000
1	1	1	2	-1.971	-106.56	13.319	3.123	0.000	3.323	0.000	3.323	0.000
1	1	2	2	-1.971	-109.31	13.299	3.123	0.000	3.323	0.000	3.323	0.000
1	1	3	2	-1.971	-112.06	13.280	3.123	0.000	3.323	0.000	3.323	0.000
1	1	4	2	-1.971	-114.81	13.261	3.123	0.000	3.323	0.000	3.323	0.000
1	2	1	2	-1.971	-106.56	13.319	3.123	0.000	3.323	0.000	3.323	0.000
1	2	2	2	-1.971	-109.31	13.299	3.123	0.000	3.323	0.000	3.323	0.000
1	2	3	2	-1.971	-112.06	13.280	3.123	0.000	3.323	0.000	3.323	0.000
1	2	4	2	-1.971	-114.81	13.261	3.123	0.000	3.323	0.000	3.323	0.000
	etc.											
2	40	1	2	-2.477	-118.96	16.708	3.323	0.000	3.323	0.000	3.323	0.000
2	40	2	2	-2.477	-120.17	16.699	3.323	0.000	3.323	0.000	3.323	0.000
2	40	3	2	-2.477	-121.38	16.691	3.323	0.000	3.323	0.000	3.323	0.000
2	40	4	2	-2.477	-122.58	16.683	3.323	0.000	3.323	0.000	3.323	0.000

6.0 Geometry and Aerodynamics Setup Files

6.1 Wing Geometry Setup Utility

The wing geometry input parameters must be specified and formatted for use in the *in_wing*x.txt* files. For 3d-analyses using MVL-15, each lifting surface (wing) is modeled as a group of contiguous panels extending in the spanwise direction starting from the wing-root and ending at the right-side wing-tip. A maximum of nine panels per wing can be defined and each panel must be associated with 2d-section properties defined in the *in_2d_aero.txt* and *in_2d_geom.txt* files. The user must specify other input parameters associated with each panel, such as the dihedral, leading edge sweep angle, and the inboard and outboard chord lengths of each panel. Note that the dihedral, sweep, and chord length are modeled separately and the parameter values of each panel are considered independently of any adjacent panels.

6.1.1 Wing Panel Geometry Calculations

The *Wing Geometry Setup Utility* can be used to help determine the parameter values needed to build the *in_wing*x.txt* input files. In some cases, the wing geometry setup is simple, but in cases with multiple panels or winglets, the utility provides feedback that the user is generating a consistent set of inputs. The utility automatically converts the user inputs to coordinates and then creates panel edge vectors. From these vectors, surface areas, projected surface areas, and other wing parameters are automatically calculated to provide geometry feedback. Figure 1 illustrates the airplane wing geometry parameters that can be input to Table 26. The utility file automatically updates related quantities so the input values can be assessed and revised, if necessary, to obtain parameter values suitable for the *in_wing1x.txt* and *in_wing*x.txt* input files.

6.1.2 Flap Geometry Definitions

The *Wing Geometry Setup Utility* also can be used to help determine the extent of the flaps on the wing panels. These steps are critical, as changes to the wing section geometry must be analyzed as unique airfoil geometry variants in order to model cruise, takeoff, and approach configurations. The user must specify the retracted flap chord length, c_{fr}, the retracted flap extension factor, c_{fx}, and the flap deflection angle, δ_f. Assuming that the nominal non-dimensional chord length, c_o, is equal to 1.0, the resultant deployed flap chord length, c_{fxr}, is given by the equation: $c_{fxr} = (c_o - c_{fr}) + c_{fr}\,(c_{fx})$. Note that the term $(c_o - c_{fr})$ is the distance from the leading edge to the flap hinge line. The resultant deployed flap chord is considered with the flap hinge line and deflection angle to determine the length of the deployed flap chord, c_{fp}, as projected on the horizontal plane. The airfoil coordinates (x, z) and the airfoil slope (dz/dx) are then non-dimensionalized with reference to c_{fp} to create modified geometry tables (file: *in_2d_geom.txt*) that are suitable for airfoil analyses. After the αzl results have been obtained for each flap geometry variant, the 2d-aerodynamics tables can be updated as described in Section 6.2.2.

The 2d-projected flap chord, c_{fp}, dictates the c_{flap} (file: *in_wing1x.txt*) input parameter value for 3d-analyses using the particular section geometry. This provides a method to capture changes in wing section geometry and the accompanying adjustments required for non-dimensionalizing the 2d-aerodynamics. During 3d-analyses, the values of the 2d-projected flap chord, c_{fp}, are not available in the non-dimensional *in_2d_geom.txt* file associated with particular wing sections. The *Wing Geometry Setup Utility* and the *2d-Variants Utility* can be utilized to clarify the definitions of the various flap parameters, and to automatically calculate a consistent set of input parameter values. The wing flap geometry parameter values specified for the airplane validation tests of this report are shown in Table 27 (takeoff) and Table 28 (approach).

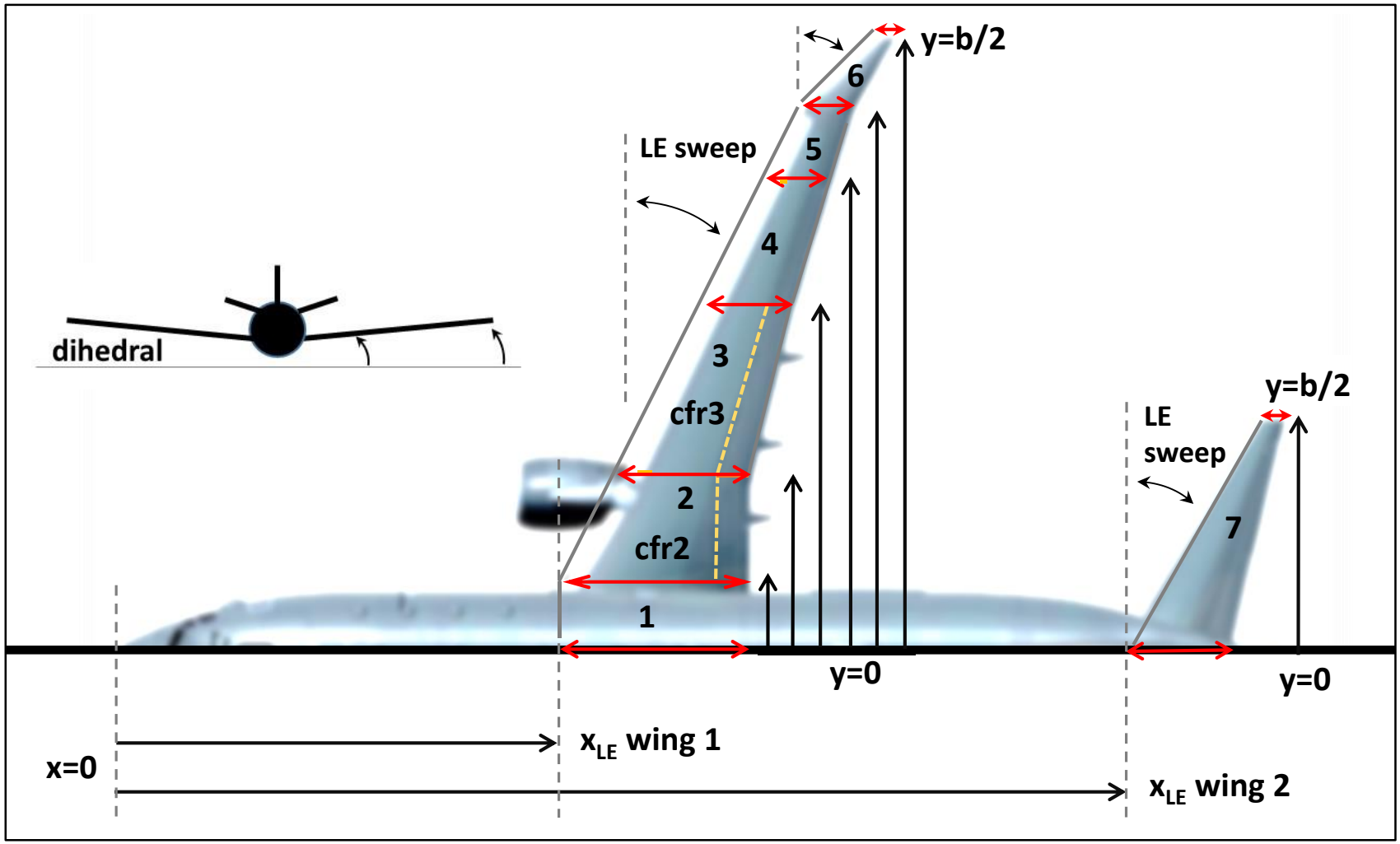


Figure 1. Airplane layout and wing parameters.

Table 26. Wing Geometry Setup Example

Wing	dihedral deg	sweep LE, deg	sweep TE, deg	y in, ft 0.0	y out, ft 62.5	2y/b in 0.0	2y/b out 1.0	z in 0.0	z out 13.6	ct/co 0.255	cbar 13.6	c(y) in 21.7	c(y) out 1.4	cf/c -	X LE -40.0	X TE -61.7	1602.1 Sw (n)	Σ5n
panel 1	*6.0*	*0.0*	0.0	*0.0*	*6.0*	0.000	0.096	*7.0*	7.6	-	-	*21.7*	*21.7*	*1.0*	*-40.0*	-61.7	260.4	
panel 2	*6.0*	*28.1*	11.5	6.0	*16.0*	0.096	0.256	7.6	8.7	-	-	21.7	*18.4*	*1.0*	-45.3	-63.7	403.2	
panel 3	*6.0*	*28.1*	11.5	16.0	*34.0*	0.256	0.544	8.7	10.6	-	-	18.4	*12.5*	*1.0*	-55.0	-67.4	558.5	
panel 4	*6.0*	*28.1*	11.5	34.0	*47.0*	0.544	0.752	10.6	11.9	-	-	12.5	*8.2*	*1.0*	-61.9	-70.1	269.6	
panel 5	*6.0*	*28.1*	11.6	47.0	*55.0*	0.752	0.880	11.9	12.8	-	-	8.2	*5.5*	*1.0*	-66.2	-71.7	110.4	
wing tip	*6.0*	*49.8*	32.5	55.0	*62.5*	0.880	1.000	12.8	13.6	-	-	5.5	*1.4*	-	-75.1	-76.5	52.3	
...etc	-	-	(checks)	-	-	-	-	-	-	-	-	-	-	-	-	-	1654.4	Σ6n
...panel n	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1646.8	Σ6n proj
...winglet	0.0	0.0	32.5	55.0	62.5	0.880	1.000			0.258	0.0	0.0	0.0	1.0	-76.5	-76.5	52.3	

Table 27. Wing Geometry Setup Example: Takeoff Flaps

Takeoff	mid	fuse	p2	p2	p3	p3	p4	p4	p5	p5	p6	p6
	y in	y out	y in	y out	y in	y out	y in	y out	y in	y out	y in	y out
Linked >	0.00	6.00	6.00	16.00	16.00	34.00	34.00	47.00	47.00	55.02	55.02	62.50
	dy:	6.00	dy:	10.00	dy:	18.00	dy:	13.00	dy:	8.02	dy:	7.48
d (flap)	F1 in			F1 out	F2 in	F2 out						
deg flap	10.0	10.0	10.0	10.0	15.0	15.0	15.0	15.0	0.0	0.0	0.0	0.0
cfr % co	18.0	18.0	18.0	18.0	15.0	15.0	15.0	15.0	0.0	0.0	0.0	0.0
cfx / cfr	1.200	1.200	1.200	1.200	1.400	1.400	1.400	1.400	0.000	0.000	0.000	0.000
cflp / co	1.0250	1.0250	1.0250	1.0250	1.0450	1.0450	1.0000	1.0000	1.000	1.000	1.000	1.000
cfx / co	0.2160	0.2160	0.2160	0.2160	0.2100	0.2100	0.2100	0.2100	0.000	0.000	0.000	0.000
cos (cfx / co)	0.2127	0.2127	0.2127	0.2127	0.2028	0.2028	0.2028	0.2028	0.000	0.000	0.000	0.000
c (y)	c in	c out	c in	c out	c in	c out	c in	c out	c in	c out	c in	c out
co	21.700	21.700	21.700	18.400	18.400	12.459	12.459	8.168	8.168	5.523	5.523	1.425
co-cfr	17.794	17.794	17.794	15.088	15.640	10.590	10.590	6.943	8.168	5.523	5.523	1.425
cfr	3.906	3.906	3.906	3.312	2.760	1.869	1.869	1.225	0.000	0.000	0.000	0.000
cfx	4.687	4.687	4.687	3.974	3.864	2.616	2.616	1.715	0.000	0.000	0.000	0.000
cos (cfx)	4.616	4.616	4.616	3.914	3.732	2.527	2.527	1.657	0.000	0.000	0.000	0.000
areas (y)	sw in	sw out	sw in	sw out	sw in	sw out	sw in	sw out	sw in	sw out	sw in	sw out
sw (co)	130.200	130.200	217.000	184.000	331.200	224.262	161.967	106.184	65.480	44.276	41.330	10.664
sw (co-cfr)	106.764	106.764	177.940	150.880	281.520	190.623	137.672	90.256	65.480	44.276	41.330	10.664
sw (cfr)	23.436	23.436	39.060	33.120	49.680	33.639	24.295	15.928	0.000	0.000	0.000	0.000
sw (cfx)	28.123	28.123	46.872	39.744	69.552	47.095	34.013	22.299	0.000	0.000	0.000	0.000
sw (cos (cfx))	27.696	27.696	46.160	39.140	67.182	45.490	32.854	21.539	0.000	0.000	0.000	0.000
Δ s(n) , Σ s(n)	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw
Sw (co)	0.000	260.400	0.000	401.000	0.000	555.462	0.000	268.151	0.000	109.757	0.000	51.994
Sw (co-cfr)	0.000	213.528	0.000	328.820	0.000	472.143	0.000	227.928	0.000	109.757	0.000	51.994
Sw (co)	0.000	260.400	0.000	401.000	0.000	555.462	0.000	268.151	0.000	109.757	0.000	51.994
Sw (cfx)	9.374	269.774	14.436	415.436	33.328	588.790	16.089	284.240	0.000	109.757	0.000	51.994
Sw (cos (cfx))	8.520	268.920	13.120	414.120	29.353	584.815	14.170	282.321	0.000	109.757	0.000	51.994
3d values	delta c	cflap	delta c	cflap	delta c	cflap	delta c	cflap	delta c	cflap	delta c	cflap
cflap	0.781	1.0360	0.722	1.0360	0.926	1.0600	0.619	1.0600	0.000	1.000	0.000	1.000
cflap (cos)	0.710	1.0327	0.656	1.0327	0.815	1.0528	0.545	1.0528	0.000	1.000	0.000	1.000
Δ Sw, Σ Sw	Σ Surface	AR, Σ Surf	Σ Projected	AR, Σ Proj	ratio, surf	ratio, proj						
Sw (co)	1654.400	9.445	1646.76	9.488	1.0000	1.0000						
Sw (cfx)	1727.627	9.044	1719.99	9.084	1.0443	1.0445						
Sw (cfx) cos	1719.563	9.087	1711.93	9.127	1.0394	1.0396						

Table 28. Wing Geometry Setup Example: Approach Flaps

Approach	mid	fuse	p2	p2	p3	p3	p4	p4	p5	p5	p6	p6
	y in	y out	y in	y out	y in	y out	y in	y out	y in	y out	y in	y out
Linked >	0.00	6.00	6.00	16.00	16.00	34.00	34.00	47.00	47.00	55.02	55.02	62.50
	dy:	6.00	dy:	10.00	dy:	18.00	dy:	13.00	dy:	8.02	dy:	7.48
d (flap)	F1 in			F1 out	F2 in	F2 out						
deg flap	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	0.0	0.0	0.0	0.0
cfr % co	18.0	18.0	18.0	18.0	15.0	15.0	15.0	15.0	0.0	0.0	0.0	0.0
cfx / cfr	1.200	1.200	1.200	1.200	1.400	1.400	1.400	1.400	0.000	0.000	0.000	0.000
cflp / co	1.0250	1.0250	1.0250	1.0250	1.0450	1.0450	1.0000	1.0000	1.000	1.000	1.000	1.000
cfx / co	0.2160	0.2160	0.2160	0.2160	0.2100	0.2100	0.2100	0.2100	0.000	0.000	0.000	0.000
cos (cfx / co)	0.1958	0.1958	0.1958	0.1958	0.1903	0.1903	0.1903	0.1903	0.000	0.000	0.000	0.000
c (y)	c in	c out	c in	c out	c in	c out	c in	c out	c in	c out	c in	c out
co	21.700	21.700	21.700	18.400	18.400	12.459	12.459	8.168	8.168	5.523	5.523	1.425
co-cfr	17.794	17.794	17.794	15.088	15.640	10.590	10.590	6.943	8.168	5.523	5.523	1.425
cfr	3.906	3.906	3.906	3.312	2.760	1.869	1.869	1.225	0.000	0.000	0.000	0.000
cfx	4.687	4.687	4.687	3.974	3.864	2.616	2.616	1.715	0.000	0.000	0.000	0.000
cos (cfx)	4.248	4.248	4.248	3.602	3.502	2.371	2.371	1.555	0.000	0.000	0.000	0.000
areas (y)	sw in	sw out	sw in	sw out	sw in	sw out	sw in	sw out	sw in	sw out	sw in	sw out
sw (co)	130.200	130.200	217.000	184.000	331.200	224.262	161.967	106.184	65.480	44.276	41.330	10.664
sw (co-cfr)	106.764	106.764	177.940	150.880	281.520	190.623	137.672	90.256	65.480	44.276	41.330	10.664
sw (cfr)	23.436	23.436	39.060	33.120	49.680	33.639	24.295	15.928	0.000	0.000	0.000	0.000
sw (cfx)	28.123	28.123	46.872	39.744	69.552	47.095	34.013	22.299	0.000	0.000	0.000	0.000
sw (cos (cfx))	25.488	25.488	42.480	36.020	63.036	42.683	30.826	20.209	0.000	0.000	0.000	0.000
Δ s(n) , Σ s(n)	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw	Δ sw	Σ sw
Sw (co)	0.000	260.400	0.000	401.000	0.000	555.462	0.000	268.151	0.000	109.757	0.000	51.994
Sw (co-cfr)	0.000	213.528	0.000	328.820	0.000	472.143	0.000	227.928	0.000	109.757	0.000	51.994
Sw (co)	0.000	260.400	0.000	401.000	0.000	555.462	0.000	268.151	0.000	109.757	0.000	51.994
Sw (cfx)	9.374	269.774	14.436	415.436	33.328	588.790	16.089	284.240	0.000	109.757	0.000	51.994
Sw (cos (cfx))	4.105	264.505	6.321	407.321	22.399	577.861	10.813	278.964	0.000	109.757	0.000	51.994
3d inputs	delta c	cflap	delta c	cflap	delta c	cflap	delta c	cflap	delta c	cflap	delta c	cflap
cflap	0.781	1.0360	0.722	1.0360	0.926	1.0600	0.619	1.0600	0.000	1.000	0.000	1.000
cflap (cos)	0.342	1.0158	0.316	1.0158	0.622	1.0403	0.416	1.0403	0.000	1.000	0.000	1.000
Δ Sw, Σ Sw	Σ Surface	AR, Σ Surf	Σ Projected	AR, Σ Proj	ratio, surf	ratio, proj						
Sw (co)	1654.400	9.445	1646.76	9.488	1.0000	1.0000						
Sw (cfx)	1727.627	9.044	1719.99	9.084	1.0443	1.0445						
Sw (cfx) cos	1698.037	9.202	1690.40	9.243	1.0264	1.0265						

6.2 MVL-15 2d-Variants Utility

If the user can access and input viscous aerodynamic data for varied and numerous airfoil types, both with and without flaps, many of the features of this utility are unncessary. In practice, the analyst will adapt airfoils based on feedback obtained from the 3d-analysis results of the wing spanwise lift distribution. This typically involves the need to adjust the incidence angle of the mean camber line for some wing panel sections. When flaps are considered, the section geometry varies as a result of changing the retracted flap chord c_{fr}, the extended flap chord, c_{fx}, the incidence angle of the mean camber line, δsi, and the flap deflection angle, δ_f. The *2d-Variants Utility* was developed to account for the practical need to vary the section geometry for the analysis of wing planforms or airplane configurations. Given nominal airfoil geometry and associated viscous aerodynamic data, the *2d-Variants Utility* can be used to generate section geometry variants and modified viscous 2d-aerodynamics tables.

6.2.1 Airfoil Geometry Generator

The user has the ability to set the values of four input parameters that control how the geometry can be varied. These parameters are the section incidence angle, the retracted flap chord ratio, the extended flap chord ratio, and the flap deflection. Each time the user modifies one of the parameters, the user can click a button which executes code that will automatically generate and name a geometry variant file. A list of the geometry variant files is saved on a worksheet in the utility file that includes the file name, a description of the geometry variant, and a dated time stamp.

After the geometry variants have been generated, the nominal geometry and the geometry of each geometry variant are analyzed as a two-dimensional airfoil by MVL-15. The primary 2d-analysis result is the airfoil angle of attack at which the lift coefficient is zero, αzl. The αzl parameter is a required component of the viscous aerodynamics tables (file: *in_2d_aero.txt*). The parameter is utilized to account for the effects of section incidence and camber as an angle of attack offset that can be listed in the 2d-aerodynamics tables. Thus, αzl is the common reference needed for correlating the airfoil viscous 2d-aerodynamics to the inviscid 3d-vortex-lattice results at each spanwise section.

6.2.2 Airfoil Aerodynamics Modifications

The *2d-Variants Utility* provides a method to shift the viscous aerodynamics tables to reflect geometry variants that introduce small changes to the section incidence angle. The lift coefficient as a function of angle of attack is adjusted based values of αzl determined by MVL-15 for the nominal and the variant geometry, and with reference to the tabulated data value of αzl. The drag coefficient is adjusted by first defining a 2^{nd} order curve fit through the nominal section drag coefficient data as a function of the nominal section lift coefficient. Updated lift coefficients associated with the updated αzl then can be used as the independent variable of the 2^{nd} order curve fit in order to calculate revised nominal drag coefficients.

The *2d-Variants Utility* also features a more complicated empirical method that was determined to be suitable for revising the viscous aerodynamics tables associated with airfoil geometry variants utilizing double-slotted flaps. The method was developed based on the analysis of data from Reference 4. The variation of C_d as a function of C_l is approximately 2^{nd} order throughout the range of flap settings associated with clean, takeoff, and approach configurations. The vertex represents the minimum-drag, C_{do}, attainable at a given flap deflection. The value of C_{do}, increases as the flap deflection angle increases and shifts to higher values of C_l. A 2^{nd} order mathematical representation was derived and then reduced to a form that correlated the minimum drag constant, C_{do}, to specific flap deflections. Thus, nominal 2d-aerodynamics tables can be modified to capture the effects of flaps in a consistent and predictable manner.

When considering flaps, it is also important to model the effects of the geometry variants on αzl, the maximum lift coefficient, and the angle at which the maximum lift occurs. Several corrections are implemented within the *2d-Variants Utility* to account for these effects. The un-modified results are first adjusted by assuming that leading edge slats are deployed during takeoff and approach flight conditions, effecting a zero-lift angle shift to higher angles of attack. Subsequent corrections to the maximum lift coefficient and the angle of maximum lift are then applied to the original slats correction, to obtain the final result. Performing a proper analysis of a wing planform or airplane configuration, without modeling these effects, is not achievable. Figure 2 illustrates some of the functionality and feedback that is available to the user when generating 2d-geometry variants from a nominal airfoil.

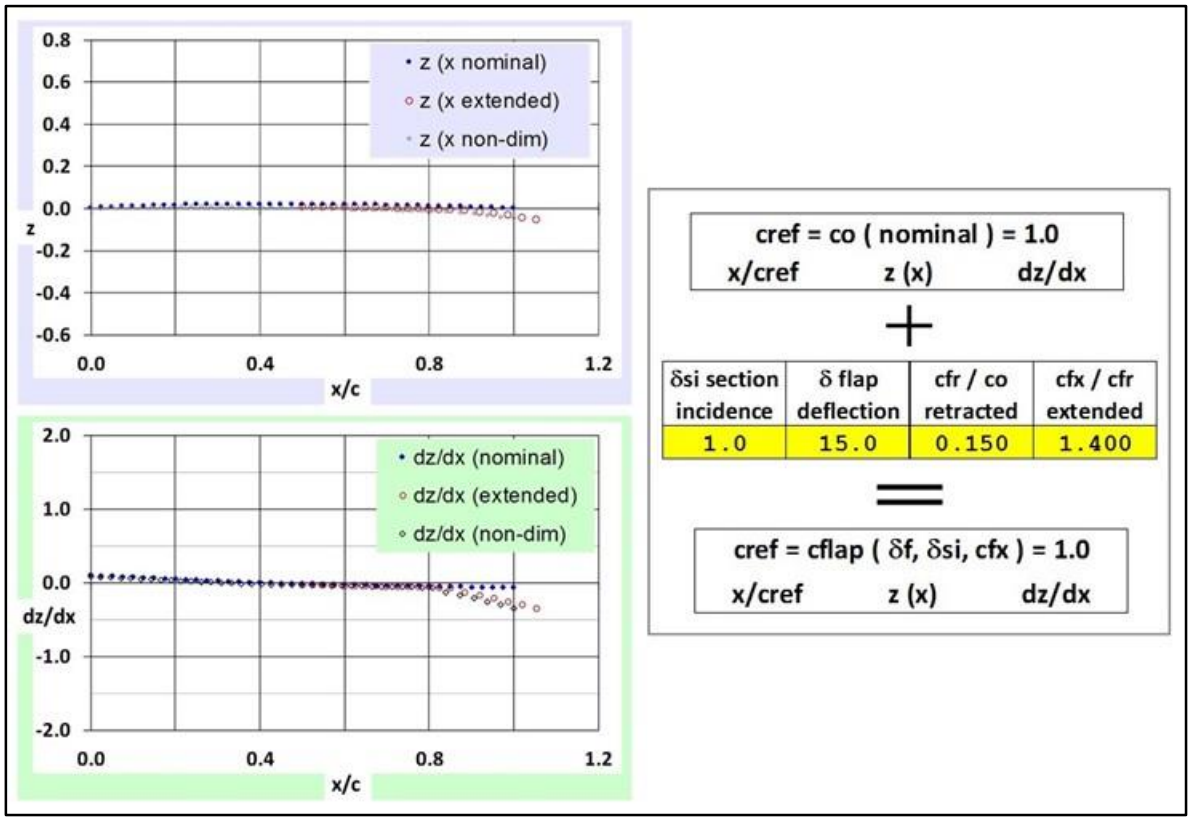


Figure 2. Airfoil parameters: section incidence and flaps.

7.0 Analysis and Results Presentation

The output files generated by MVL-15 provide comprehensive details of the analysis. The output files and the tabulated results are grouped and formatted to simplify assessment of the results, but visualizing the results as charts depicting the geometry, spanwise aerodynamics, and integrated aerodynamics can enhance the interpretation and presentation of the results. Throughout the development of MVL-15 and in the course of interpreting results output, the most useful and frequently generated tables and charts were collected and saved as separate worksheets in an Excel file. The following sections describe the content and utility of the MVL-15 *3d-Results Presentation Utility* file, with the understanding that application of this utility is optional and that other users may choose to portray the results differently.

7.1 MVL-15 3d-Results Presentation Utility

The MVL-15 *3d-Results Presentation Utility* provides a basic automated capability for reading the MVL-15 output and generating charts and tables suitable for visualizing and presenting results. The automation is accomplished using an Excel Visual Basic code that accesses MVL-15 output files and transfers analysis results to pre-determined cells on various worksheets of the utility file. The "Geometry", "Aerodynamics Tables", "Spanwise (2y/b)", and "Polars-Sref-noflaps" are the primary worksheets of the MVL-15 *3d-Results Presentation Utility* file. The automated code can be executed by clicking a prominent control button on the "Aerodynamics Tables" worksheet. After the user executes an update, the Excel Visual Basic code does not automatically save the *3d-Results Presentation Utility* file. Thus, the processed results can be reviewed before the analyst elects to "save", "modify-save", or "close-without-saving".

There are few accommodations within the code to facilitate chart format revisions that might be desired based on the results output. For this reason, simple variations of the tool can be created to eliminate the manual adjustments needed to accommodate the range of output values that might be encountered during various analyses. For example, one version of the utility file, intended for visualizing 2d-geometry results, might be scaled for a chord length of 1.0 ft; whereas a similar version intended for visualizing 3d-airplane configuration results might be scaled for an airplane length of 100 ft.

Figure 3 summarizes the group of output charts that can be used to visualize airfoil, wing, and airplane configuration analysis results. Additional details and separate consideration of each of the elements depicted in Figure 3 are provided in the following sections. Separate validation results regarding the geometry, spanwise aerodynamics, and integrated aerodynamics are provided throughout Section 8.

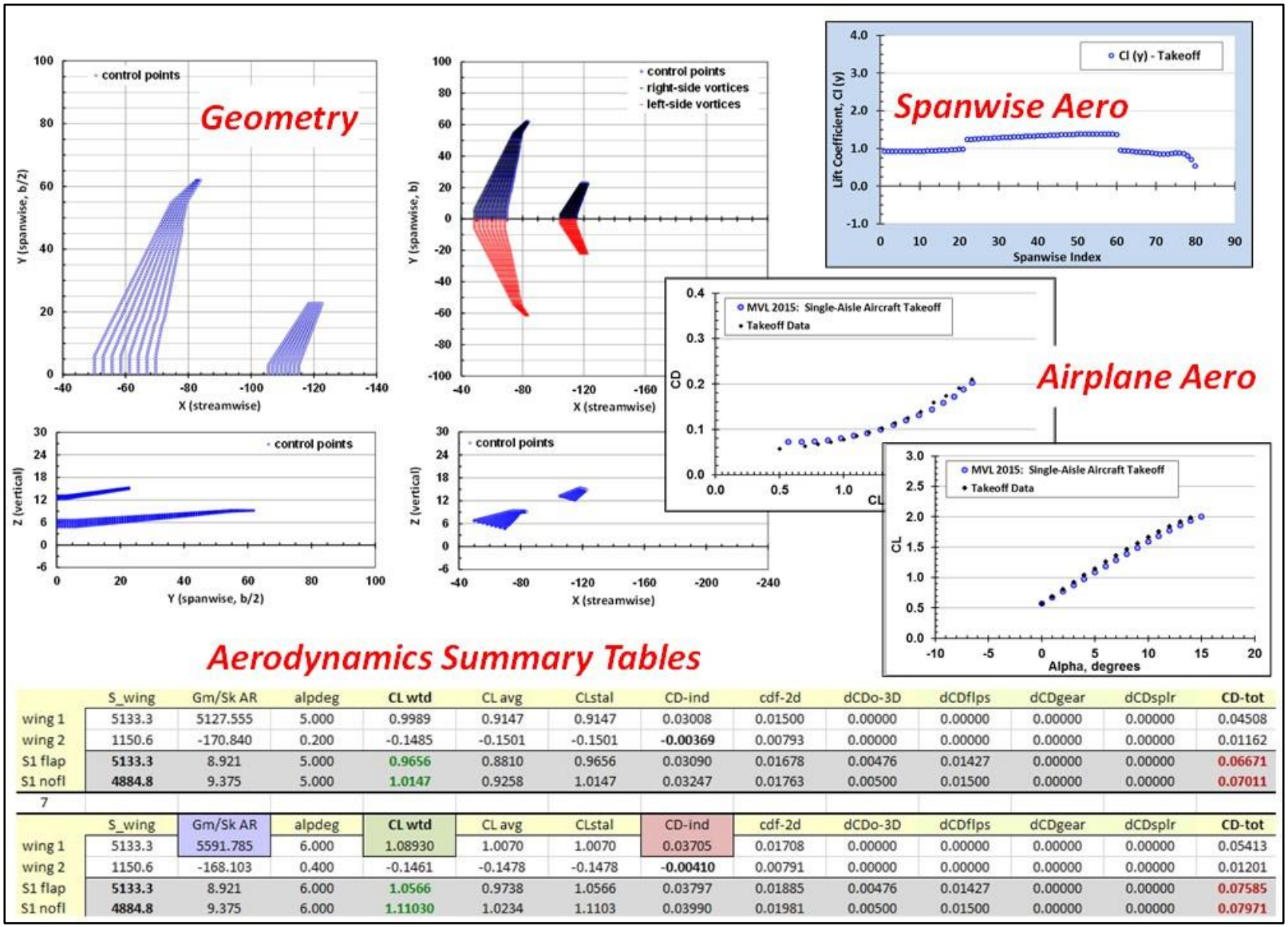
7.1.1 Geometry Charts

The analysis geometry tabulated in the *out_geom.txt* file, at the output angle of attack specified by the input parameter, *alfput* (file: *in_alphas.txt*) are copied to the "Geometry" worksheet. The results enable the user to view charts of the MVL-15 analysis geometry, as projected to the X-Y, X-Z, and Y-Z planes. Two views are available the X-Y plane; the lattice control point locations are shown in the half-span view, whereas the lattice control points and the left- and right- inner-vortex locations are shown in the full-span view. When assessing only the geometry (and not the aerodynamics), a secondary control button is available on the "Geometry" worksheet that can be clicked to update only the geometry charts.

7.1.2 Aerodynamics Summary Tables

Most of the tabulated results of the *out_aero.txt* file are replicated on the "Aerodynamics Tables" worksheet, but some information is parsed for use on the "Spanwise (2y/b)", "Polars-Sref-noflaps", and "Polars-Sref-flaps" worksheets. Clicking the main control button located on this page will automatically

update all of the following worksheets: “Geometry”, “Aerodynamics Tables”, “Spanwise (2y/b),” and “Polars-Sref-noflaps”, and the hidden worksheet: “Polars-Sref-flaps”. The format and content of the aerodynamics output table is automatically updated for analyses completed with 20 or fewer angles of attack (i.e., 1 < = *nalphas* (file: in_alphas.txt) < = 20. The reformatting is necessary to ensure the proper output values are sent to the “Spanwise (2y/b),” “Polars-Sref-noflaps”, and “Polars-Sref-flaps” worksheets.



Aerodynamics Summary Tables

	S_wing	Gm/Sk AR	alpdeg	CL wtd	CL avg	CLstal	CD-ind	cdf-2d	dCDo-3D	dCDflps	dCDgear	dCDsplr	CD-tot
wing 1	5133.3	5127.555	5.000	0.9989	0.9147	0.9147	0.03008	0.01500	0.00000	0.00000	0.00000	0.00000	0.04508
wing 2	1150.6	-170.840	0.200	-0.1485	-0.1501	-0.1501	**-0.00369**	0.00793	0.00000	0.00000	0.00000	0.00000	0.01162
S1 flap	**5133.3**	8.921	5.000	0.9656	0.8810	0.9656	0.03090	0.01678	0.00476	0.01427	0.00000	0.00000	0.06671
S1 nofl	**4884.8**	9.375	5.000	1.0147	0.9258	1.0147	0.03247	0.01763	0.00500	0.01500	0.00000	0.00000	0.07011
7													
	S_wing	Gm/Sk AR	alpdeg	CL wtd	CL avg	CLstal	CD-ind	cdf-2d	dCDo-3D	dCDflps	dCDgear	dCDsplr	CD-tot
wing 1	5133.3	5591.785	6.000	1.08930	1.0070	1.0070	0.03705	0.01708	0.00000	0.00000	0.00000	0.00000	0.05413
wing 2	1150.6	-168.103	0.400	-0.1461	-0.1478	-0.1478	**-0.00410**	0.00791	0.00000	0.00000	0.00000	0.00000	0.01201
S1 flap	**5133.3**	8.921	6.000	1.0566	0.9738	1.0566	0.03797	0.01885	0.00476	0.01427	0.00000	0.00000	0.07585
S1 nofl	**4884.8**	9.375	6.000	1.11030	1.0234	1.1103	0.03990	0.01981	0.00500	0.01500	0.00000	0.00000	0.07971

Figure 3. MVL-15 *3d-Results Presentation Utility* (airplane takeoff example).

7.1.3 Spanwise Aerodynamics, with Charts

The spanwise aerodynamics tabulated in the *out_span.txt* file, at the output angle of attack specified by the *alfput* parameter of the *in_alphas.txt* input file, are copied to the "Spanwise (2y/b)" worksheet. The number of rows linked to the spanwise output chart is set to 80 by default. Other aspects of this worksheet limit the maximum number of rows to 100. The user can choose to revise the worksheet or accommodate the formatting issue by judiciously specifying the value of the *ipts-k* (file: *in_wing*x.txt*) input parameter. If two or more wings are analyzed, and the total number of spanwise stations is less than 80, the spanwise aerodynamics of each wing will be shown on the spanwise aerodynamics charts. In such cases, note that as ordered in the output and utility files, results for wing-2 will be plotted as though positioned outboard of wing-1 and by extension, results for wing-n will be plotted as though positioned outboard of wing-(n-1). In addition to the spanwise lift, secondary charts depicting the spanwise angle of attack, induced angle of attack, and bound circulation are also available.

7.1.4 Integrated Aerodynamics, C_D vs. C_L and C_L vs. α

Selected values from the aerodynamics summary tables are processed to create new tables that are suitable for generating drag polar and lift curve charts for a wing planform or vehicle configuration. Two tables are generated at all analysis angles of attack listed for wing-1, and are saved on separate worksheets. Aerodynamic coefficients of the first table are saved in the "Polars-Sref-noflaps" worksheet and are based on a wing-1 reference area without flaps. The aerodynamic coefficients of the second table are saved in the "Polars-Sref-flaps" worksheet and are based on a wing-1 reference area with flaps. For clarity, and since the use of the flap area as a reference area is somewhat unconventional, the worksheet containing the second table is hidden.

If the value of the *Swaero* input parameter (file: *in_wing1x.txt*) were specified to generate an additional row of results in the *out_aero.txt* file, neither of the "Polars-Sref-" worksheets will be created properly by the automated code. Two quick and simple methods are available as a work around. The user can delete all of the third, all of the fourth, or all of the fifth rows of output in the *out_aero.txt* file (at all angles of attack) and then click the main control button on the "Aerodynamics Tables" worksheet. Alternately, if the magnitude of the *Swaero* input parameter is input as negative, the tables will update normally when the main control button is clicked. When using this option, the value of the *Swaero* input parameter is listed on both polar worksheets as the reference point for manually re-calculating the aerodynamic coefficients.

7.2 Analysis Procedure: Start-to-Finish Example

Details of the MVL-15 analysis tool have been described throughout this report. The following sections are organized to highlight the main categories of the overall analysis process; each section contains a brief summary of the analysis segment.

7.2.1 Airplane Geometry Definition

The first step of the analysis is to acquire source data for the airfoil sections and vehicle configuration. For most conceptual analyses, an approximate 3-view schematic can be used to quantify parameters such as the wing span, sweep, dihedral and chord lengths. The wing planform is usually specified as a trapezoidal shape extending to the vehicle centerline, with a wing panel break at the fuselage intersection. During this phase of the analysis, the aircraft geometry is determined and formatted, with the aid of the *Wing Geometry Setup Utility* for the purpose of building the *in_wing*x.txt* input files. Wing panels with flaps must be identified so that the retracted flap chord ratios, the flap extension multipliers, and the flap deflection angles

can be specified for the takeoff and approach configurations. This process should be completed with consideration of the information and functionality available in the *Wing Geometry Setup Utility* file.

7.2.2 Section Variant Analyses

At least one prospective nominal airfoil, with known geometry and available aerodynamics data, should be obtained. The nominal airfoil geometry should be evaluated using MVL-15 to determine αzl. The αzl result should be compared to the empirical data associated with the airfoil to confirm that the nominal geometry was properly specified. For properly specified geometry, the difference between the MVL-15 αzl and the empirical data αzl should be less than about 0.5 degrees. Once verified, a number of section variants should be generated by changing the incidence angle to align the MVL-15 aerodynamics results with the empirical 2d-aerodynamics tables. Once calibrated, the 2d-aerodynamics tables can be adjusted as described in Section 6.2.2. The user should continue the process by generating the anticipated flap geometry variants and creating revised 2d-aerodynamics tables according to the aerodynamics model described in Section 6.2.2. The user should verify that the flap chord lengths, as extended, deflected, and projected are consistent with the initial wing flap chord length estimates of the *Wing Geometry Setup Utility*.

7.2.3 MVL-15 Setup and Execution

After the 2d-aerodynamics tables have been created and modified for each geometry variant, the user must compile multiple 2d-aerodynamics tables, one for each panel of each wing, to create *in_2d_geom.txt* and *in_2d_aero.txt* files suitable for the analysis of a multi-panel wing planform or airplane configuration. Next, the user specifies the analysis angles of attack and the analysis parameters. A thorough and final review of the *in_wing1x.txt* input parameter values should be completed at this point to ensure the reference areas, flap chord factors, and flight segment parameters are properly set. The final step of the process is to execute MVL-15.

7.2.4 Results Assessment

After the MVL-15 analysis has been completed at all angles of attack for the airplane configuration, the output files should be inspected and the MVL-15 *3d-Results Presentation Utility* should be used to summarize and visualize the results.

Typically, during the early phases of an analysis, the spanwise aerodynamics results provide the most insight about the suitability of the airfoil section properties, as installed on the wing. Some analysis iteration can be required when assigning various airfoil sections to the wing panels. Sometimes, it is necessary to generate new airfoil sections by increasing or decreasing the section incidence for a given wing panel. Such additional efforts usually become evident after initial spanwise aerodynamics results have been processed and reviewed. For example, the analyst may determine that modifications are necessary to obtain an efficient spanwise lift distribution on the main wing. During later phases of an analysis, the integrated results of the "Polars-Sref-noflaps" gain relevance when assessing how various specified flap configurations affect the integrated aerodynamics of the analysis configuration.

8.0 Validation Results

8.1 Available 2d-Geometry and 2d-Aerodynamics Tables

The analyses and validation tests documented in this report required creating and utilizing a variety of airfoil sections for both 2d- and 3d-analyses. Table 29 lists the reference names of the available 2d-geometry and 2d-aerodynamics files and provides information about the section characteristics. Ten 2d-geometry files are available; three are based on a flat-plate airfoil, and seven are based on a typical airfoil with camber and thickness. Six geometry variants were generated by changing only the section incidence angle (δ_{si}) of the flat-plate (+0.0, +1.0, and +6.0 degrees) and typical (+0.0, +1.0, and +7.0 degrees) airfoils. The *p1* typical airfoil was further modified by changing the flap parameters (c_{fr}, c_{fx}, δ_f, δ_{si}) to create 2d-geometry variants suitable for modeling takeoff and approach. All ten of the 2d-sections were then analyzed using MVL-15 to determine αzl. The x-z coordinates of the typical and flat-plate geometry variants are depicted graphically in Figure 4 and Figure 5.

The 2d-analysis results were incorporated into the 2d-aerodynamics tables for subsequent 3d-analyses. The section drag coefficients and lift curve slopes associated with these 2d-aerodynamics tables are plotted in Figure 6 through Figure 11 for each available airfoil section. The figures provide examples that the 2d-aerodynamics tables can be set up to model various combinations of viscosity on lift and drag (inviscid or viscous, either separately and combined).

Table 29. Available Validation Files: Airfoil Geometry and 2d-Aerodynamics Information

GEOMETRY FILES	Reference 2d-Name	Reference Figure	Characteristic	δsi (deg.)	Mean Camber (deg.)	αzl (deg.)
in_2d_geom_p0dsi	p0	Figure 4	airfoil: p0	p0: + 0.0	1.9224	-1.9224
in_2d_geom_p1dsi	p1	Figures 4 & 5	airfoil: p1	p1: + 1.0	1.9224	-2.9232
in_2d_geom_p7dsi	p7	Figure 4	airfoil: p7	p7: + 7.0	1.9224	-8.9962
in_2d_geom-flat0	f0	Figure 4	flat plate: f0	f0: + 0.0	0.0000	0.0000
in_2d_geom-flat2923	f29	Figure 4	flat plate: f29	f29: + 2.92	0.0000	-2.9232
in_2d_geom-flat6	f6	Figure 4	flat plate: f6	f6: + 6.0	0.0000	-6.0000
in_2d_geom_p1_df10_cfr18%_cfx1.2_tki	p1-tki	Figure 5	p1, cfr, cfx, δf10	Δαzl (δf10, cf) + 1	2.9232 + 0.5484	-3.4716
in_2d_geom_p1_df15_cfr15%_cfx1.4_tko	p1-tko	Figure 5	p1, cfr, cfx, δf15	Δαzl (δf15, cf) + 1	2.9232 + 2.1656	-5.0888
in_2d_geom_p1_df25_cfr18%_cfx1.2_ain	p1-ain	Figure 5	p1, cfr, cfx, δf25	Δαzl (δf25, cf) + 1	2.9232 + 5.4757	-8.3989
in_2d_geom_p1_df25_cfr15%_cfx1.4_aout	p1-aout	Figure 5	p1, cfr, cfx, δf25	Δαzl (δf25, cf) + 1	2.9232 + 4.7112	-7.6344

SECTION AERODYNAMICS TABLES	Reference 2d-Name	Reference Figure	3d-Application	Cl-α notes	αzl (deg.)	Cdf notes
in_2d_aero p0dsi	visc-p0	Figure 6	typical	1.0 stall	-1.9224	viscous
in_2d_aero p1dsi	visc-p1	Figure 6	typical	1.0 stall	-2.9232	viscous
in_2d_aero p7dsi	aero-p7	Figure 6	validate α+δsi	1.0 stall	-8.9662	viscous
in_2d_aero-azl0 cla1 visc	visc-azl0	Figure 7	validate Cdf	1.0	0.0000	viscous
in_2d_aero-azl0 cla visc stall	visc-azl0st	Figure 7	validate high-α	1.0 stall	0.0000	viscous
in_2d_aero-azl0 cla1pt5 visc	visc-azl0x5	Figure 7	validate blowing	1.5	0.0000	viscous
in_2d_aero-azl290 cla1 visc	visc-azl29	Figure 8	validate Cdf	1.0	-2.9000	viscous
in_2d_aero-azl290 cla visc stall	visc-azl29st	Figure 8	validate high-α	1.0 stall	-2.9000	viscous
in_2d_aero-azl290 cla1pt5 visc	visc-azl29x5	Figure 8	validate blowing	1.5	-2.9000	viscous
in_2d_aero-flat0	invs-f0	Figure 9	typical	1.0	0.0000	0.0
in_2d_aero-flat2923	invs-f29	Figure 9	typical	1.0	-2.9232	0.0
in_2d_aero-flat6	invs-f6	Figure 9	validate α+δsi	1.0	-6.0000	0.0
in_2d_aero-azl0	aero-0	-	typical	1.0 stall	0.0000	model: shift
in_2d_aero-azl2923	aero-29	-	typical	1.0 stall	-2.9232	model: shift
in_2d_aero_p1dsi tki	aero-p1tki	Figure 10	typical takeoff	1.0 stall	-3.4716	model: flaps
in_2d_aero_p1dsi tko	aero-p1tko	Figure 10	typical takeoff	1.0 stall	-5.0888	model: flaps
in_2d_aero_p1dsi ain	aero-p1ain	Figure 11	typical approach	1.0 stall	-8.3989	model: flaps
in_2d_aero_p1dsi aout	aero-p1aout	Figure 11	typical approach	1.0 stall	-7.6344	model: flaps

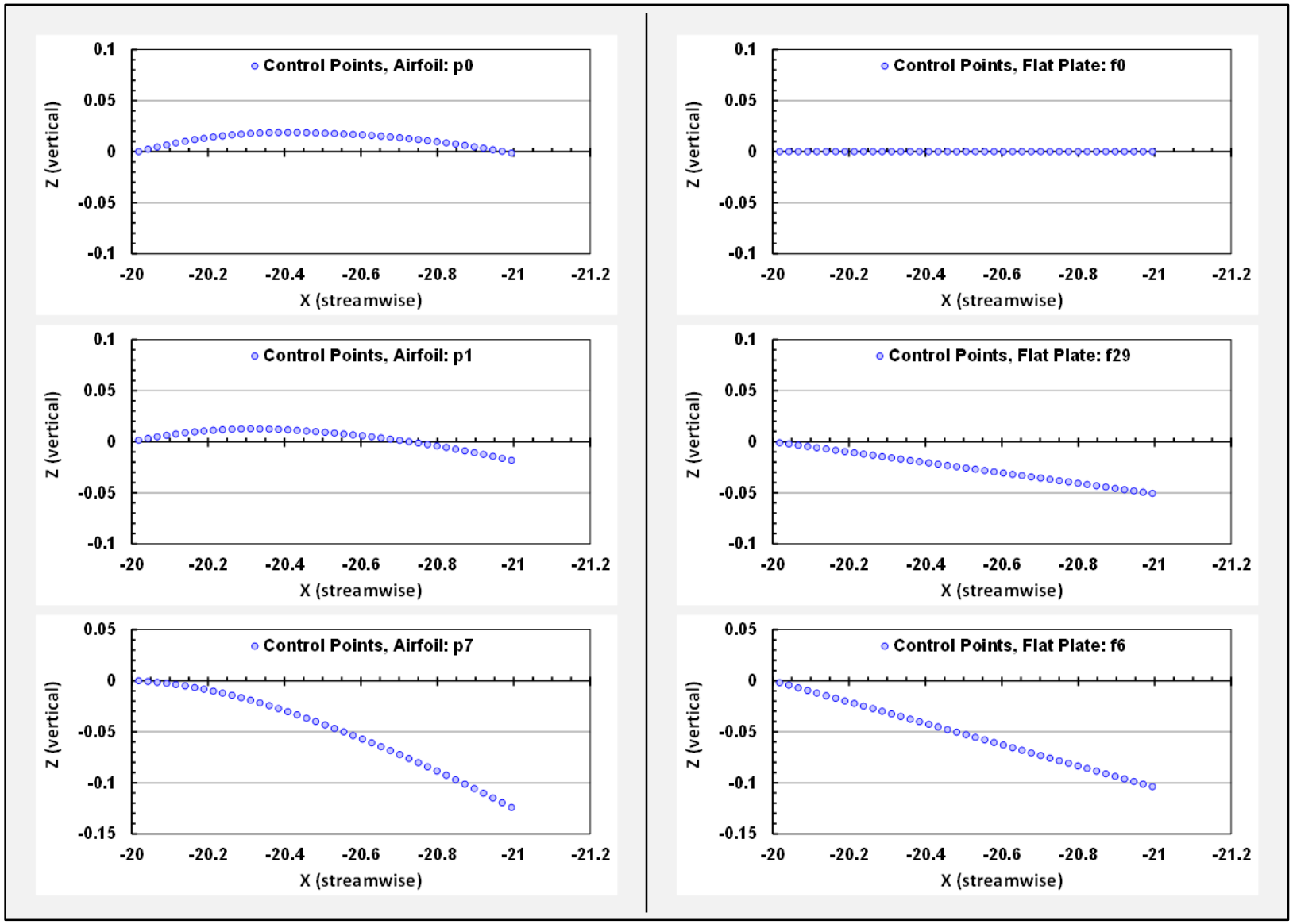


Figure 4. Airfoil geometry comparisons: airfoil and flat plate variants.

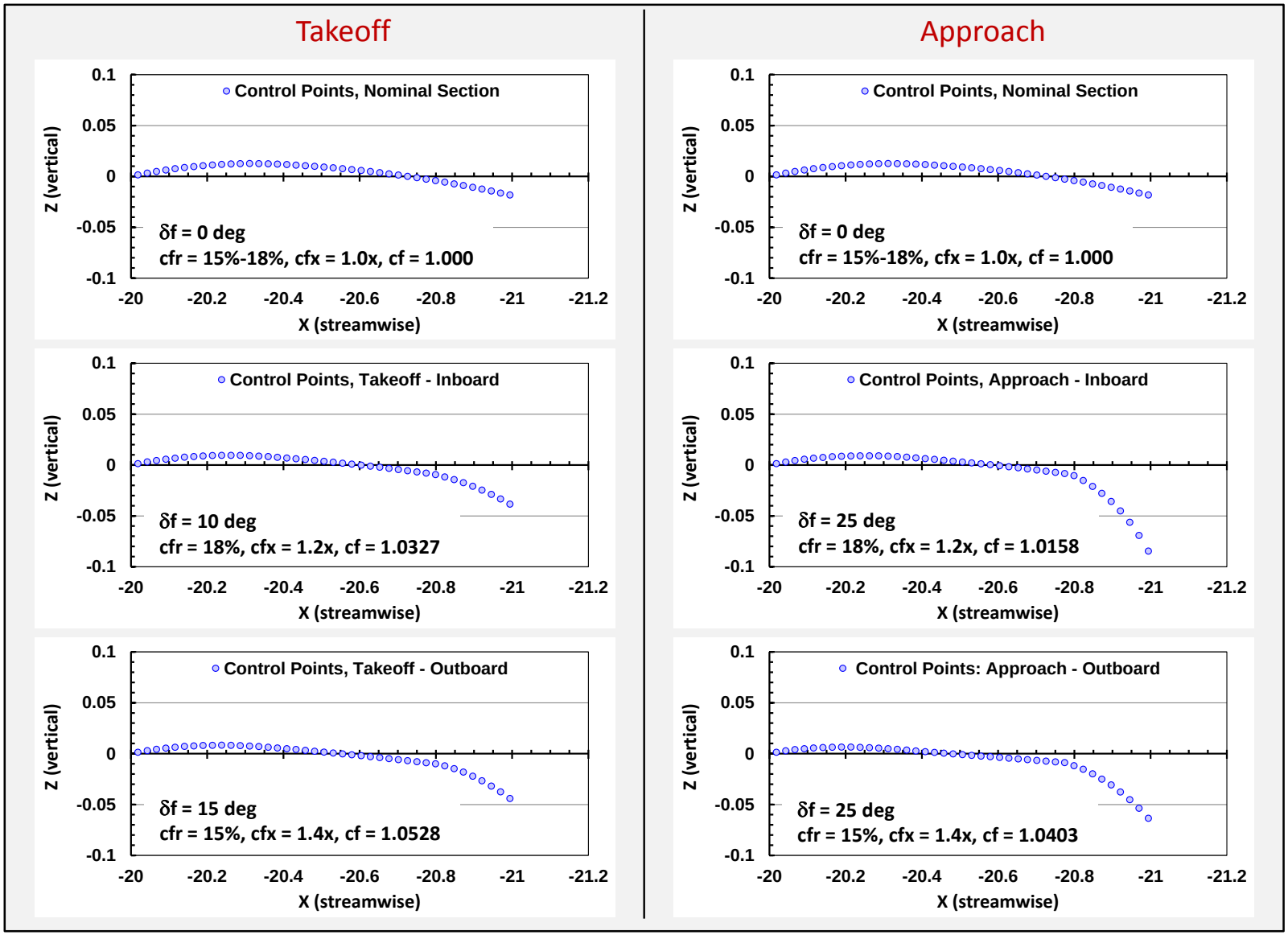


Figure 5. Section geometry comparisons: MVL-15 (2d) nominal, takeoff, and approach.

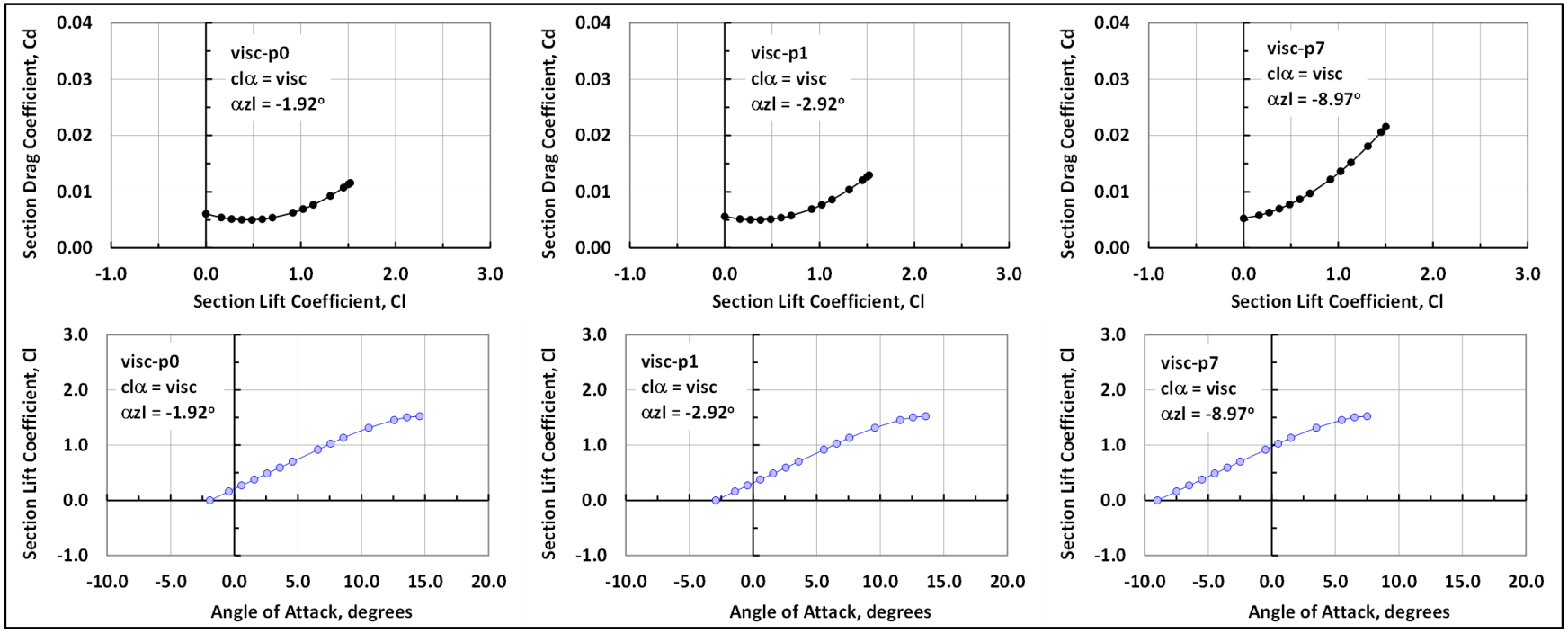


Figure 6. Example airfoil aerodynamics, p0, p1, and p7 variants.

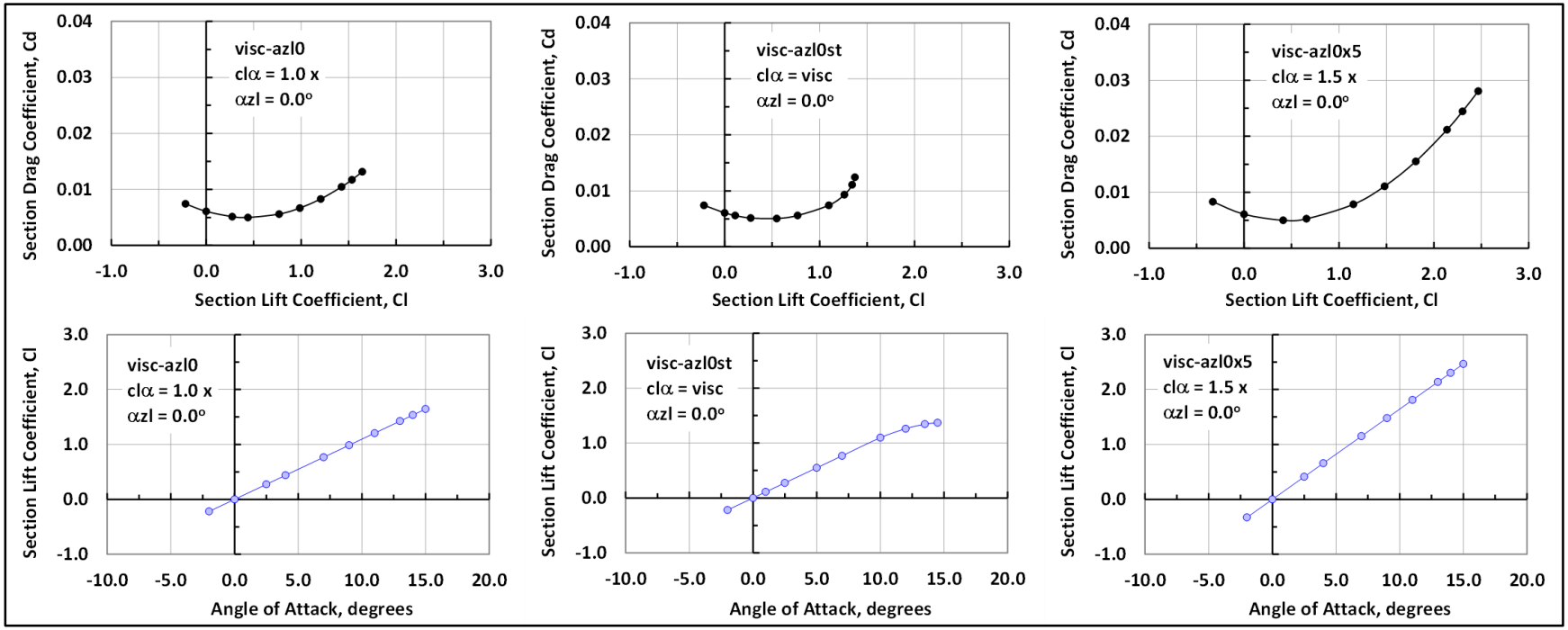


Figure 7. Example airfoil aerodynamics, αzl = 0.0 degrees.

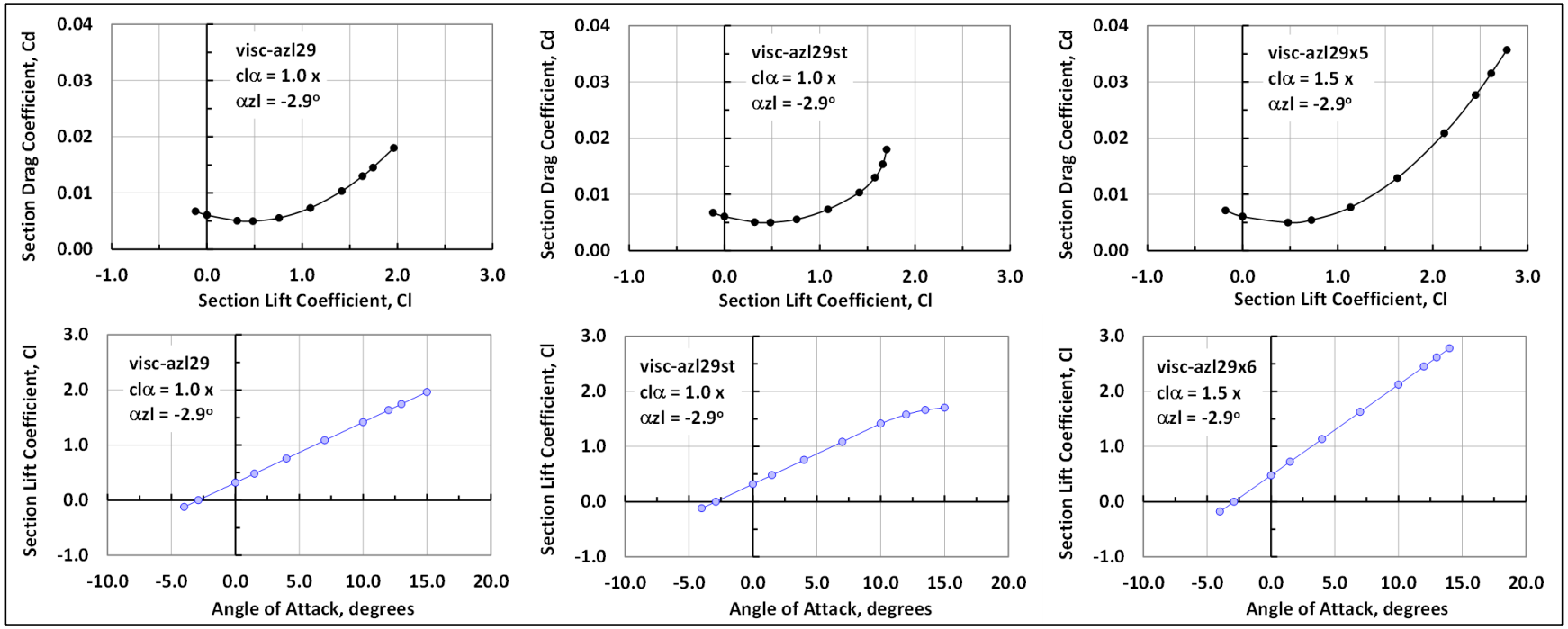


Figure 8. Example airfoil aerodynamics, αzl = -2.9 degrees.

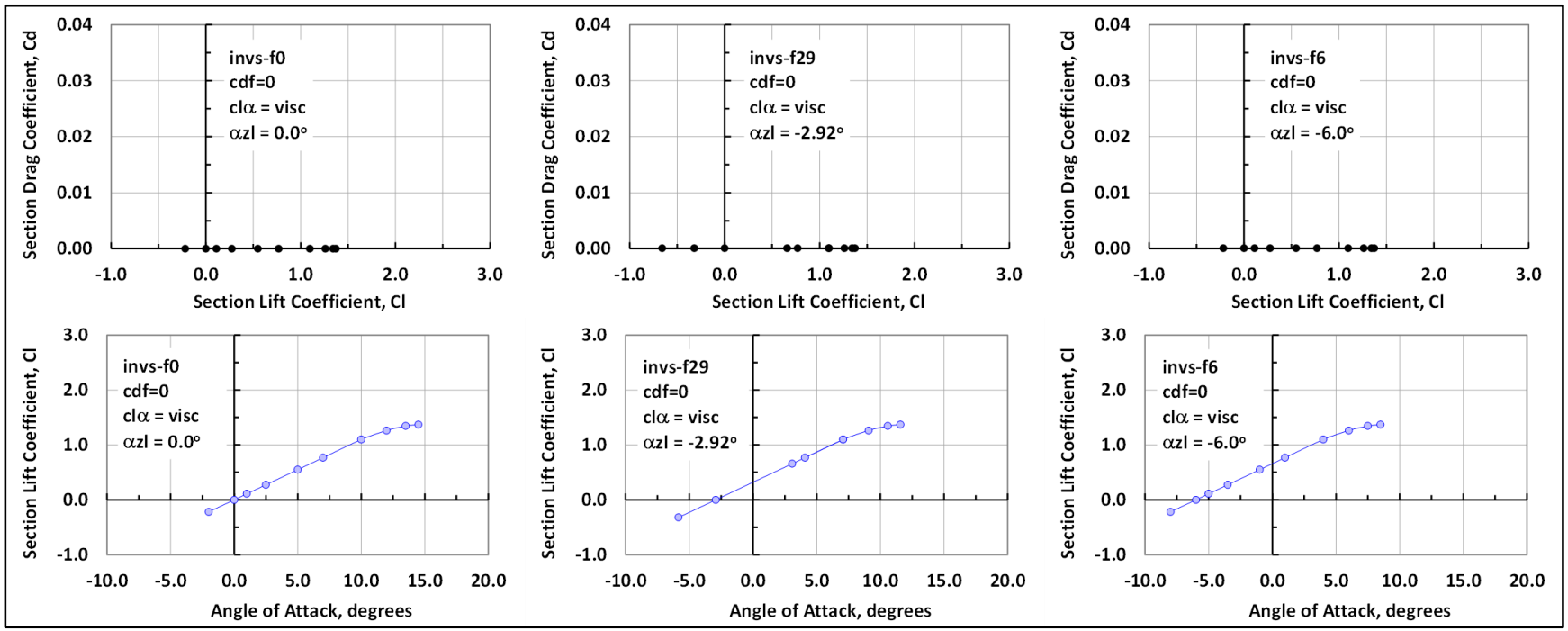


Figure 9. Example airfoil aerodynamics, f0, f29, and f6 flat-plate sections.

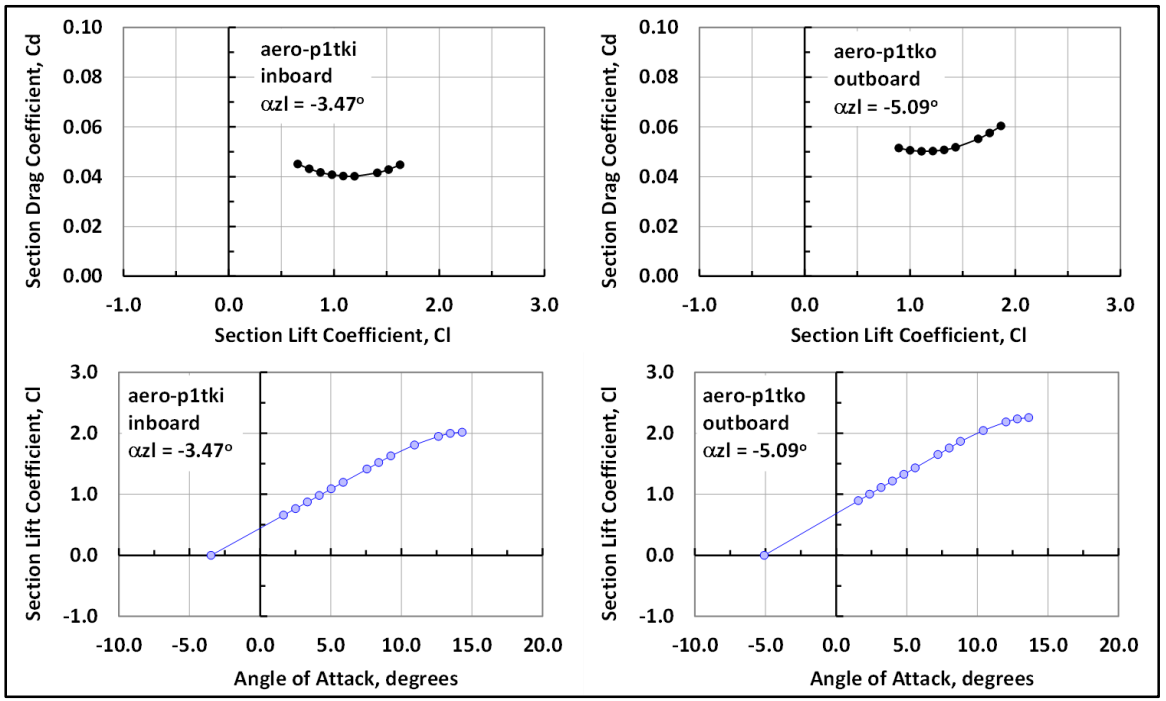


Figure 10. Example airfoil aerodynamics, takeoff flaps.

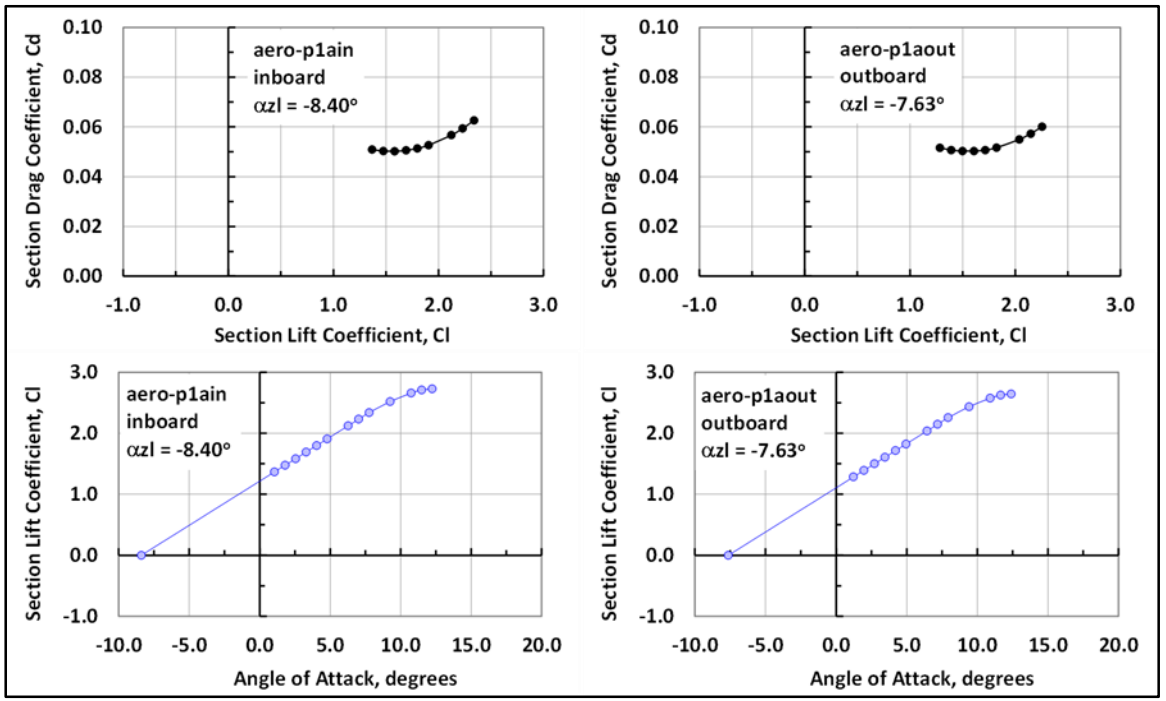


Figure 11. Example airfoil aerodynamics, approach flaps.

8.2 Airfoil and Wing Aerodynamics: Parameter Variations and 2d-Correlations

A group of analysis cases was developed to validate basic aspects of the MVL-15 methodology. The lifting surface was an AR=1000 rectangular wing (c_o=1.0, b/2=500.0), modeled as a single spanwise panel, and partitioned according to the number of spanwise, chordwise, and wing-tip lattice points specified (respectively) by the input parameters, *ipts*, *jpts*, and *nallow* (file: *in_wing1x.txt*). Both 2d- and 3d-analysis cases were evaluated and the results are summarized in Table 30.

The 2d-analysis methodology involves calculating the inviscid vortex-lattice aerodynamics for the airfoil geometry at an angle of attack of zero degrees. Although the lift coefficient is determined during this process, αzl is the key output required for creating the 2d-viscous aerodynamics tables associated with that airfoil. The 3d-analysis methodology involves calculating the inviscid vortex-lattice aerodynamics for the wing planform geometry at the specified wing α, including the offset angles introduced by α_i and the airfoil αzl, at each spanwise location of the wing. Therefore, the net local of attack is a function of α, α_i, and αzl; if flaps are deployed, the net angle of attack also depends on c_o, c_f, and the reference chord of the aerodynamic coefficients in the 2d-aerodynamics tables (at all spanwise stations). All these factors are considered when determining the net angles of attack at all spanwise locations on the wing. These angles link the inviscid 3d-vortex-lattice solution to the 2d-viscous aerodynamics tables.

In Table 30, the 2d-analyses are listed as validation Cases 1-8, and the 3d-analyses are listed as validation Cases 9-32. The validation cases are color coded; relationships between rows are indicated by matching colors, and the most relevant items within a row are indicated by red outlines. Columns 1-3 provide information about each case, and Columns 4-6 list the relevant lattice geometry input parameters. Column 7 lists the airfoil incidence (or, mean camber) angle, Column 8 lists the analysis angle of attack, and Column 9 lists the effective angle of attack resulting from the combined effects of these two angles. For visualization purposes, the first eight rows of Column 9 list $-\alpha zl$ as the 2d-effective angle of attack; it should be noted that these values were obtained from the 2d-analysis output. Columns 10-14 list selected aerodynamic results obtained from the *out_aero.txt* files.

In-depth validations of the lattice geometry were completed prior to this study; however, a number of illustrative examples (for both 2d- and 3d-analyses) can be found in Section 8.4 through Section 8.7. It will be assumed that the lattice algorithm and lattice input parameters provide the capability to properly model the analysis geometry presented in this report. The following paragraphs present questions and answers to provide insight to the rationale for creating the validation cases listed in Table 30.

Are the 2d-analysis results compatible with existing test data and aerodynamic theory?

The flat-plate airfoil results for Cases 1-4 indicate that the lift coefficient and lift-curve slope match the theoretical values expected from thin-airfoil theory. Case 2 indicates that viscous drag can be associated (not analytically determined) with the airfoil during 2d-analyses. The results for Case 5 were based on the 2d-geometry of the nominal *p0* airfoil. The incidence angle of this airfoil was increased by +1.0 degrees to obtain the nominal *p1* airfoil geometry for Cases 6-7, and by +7.0 degrees to obtain the nominal *p7* airfoil geometry for Case 8. The *p0* airfoil is based on a NACA 65-410 airfoil; the geometry and aerodynamic data are available in Reference 4. The airfoil characteristics were deemed representative and applicable to the low-speed analyses of this study. The p0 airfoil data indicate that αzl = -2.4 degrees (approximately), and the MVL-15 results indicate that αzl = -1.9 degrees. Prior analyses have indicated that increasing the number of chordwise points of the 2d-geometry model decreases the αzl difference between the airfoil data and MVL-15 results. However, this increases the analysis workload and execution time for little gain; such differences are more readily eliminated using the aerodynamics model described in Sections 6.2.2

Table 30. Airfoil and Wing Aerodynamics: Varying the Lattice Geometry, αzl, δsi, and 3d-α

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Case	Geometry Characteristics	2d-Name	Span ipts	Chord jpts	Tip nallow	Section δsi	Section α	Effective 2d α	Output 2d-αzl	Output Σ c Cl dy	Output CD-ind	Output Cdf-2d	Output CD-tot
1	flat plate: f0	invs-f0	20	41	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	flat plate: f0	visc-f0	20	41	0	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.006
3	flat plate: f29	invs-f29	20	41	0	2.923	0.000	2.923	-2.923	0.321	0.000	0.000	0.000
4	flat plate: f6	invs-f6	20	41	0	6.000	0.000	6.000	-6.000	0.662	0.000	0.000	0.000
5	airfoil: p0	visc-p0	20	41	2	0.000	0.000	1.922	-1.922	0.211	0.000	0.006	0.006
6	airfoil: p1	visc-p1	20	41	2	1.000	0.000	2.923	-2.923	0.321	0.000	0.006	0.006
7	airfoil: p1	visc-p1	80	41	0	1.000	0.000	2.923	-2.923	0.321	0.000	0.006	0.006
8	airfoil: p7	visc-p7	20	41	2	7.000	0.000	8.996	-8.996	0.987	0.000	0.006	0.006
Case	Analysis Comments	Compare w/ 2d-Name	Span ipts	Chord jpts	Tip nallow	Input 2d-αzl	Wing α	Effective 3d α	Output α	Output Σ c Cl dy	Output CD-ind	Output Cdf-2d	Output CD-tot
9	α=2.923 αzl=f0	invs-f0	80	9	0	0.000	2.923	2.923	2.923	0.318	0.000	0.000	0.000
10	α=2.923 αzl=f0	visc-f0	80	9	0	0.000	2.923	2.923	2.923	0.318	0.000	0.005	0.005
11	α=0 αzl=f29	invs-f29	80	9	0	-2.923	0.000	2.923	0.000	0.319	0.000	0.000	0.000
12	α=0 αzl=f6	invs-f6	80	9	0	-6.000	0.000	6.000	0.000	0.656	0.000	0.000	0.000
13	α=0 αzl=p0	visc-p0	20	41	0	-1.922	0.000	1.922	0.000	0.204	0.000	0.006	0.006
14	α=0 αzl=p0	visc-p0	20	41	2	-1.922	0.000	1.922	0.000	0.200	0.000	0.006	0.006
15	α=1.922 αzl=f0	visc-p0	20	41	0	0.000	1.922	1.922	1.922	0.207	0.000	0.006	0.006
16	α=1.922 αzl=f0	visc-p0	20	41	2	0.000	1.922	1.922	1.922	0.203	0.000	0.006	0.006
17	α=0 αzl=p1	visc-p1	20	41	2	-2.923	0.000	2.923	0.000	0.309	0.000	0.005	0.006
18	α=-2.923 αzl=p1	visc-p1	20	41	2	-2.923	-2.923	0.000	-2.923	0.000	0.000	0.006	0.006
19	α=0 ntip0 jpts9	visc-p1	20	9	0	-2.923	0.000	2.923	0.000	0.315	0.000	0.005	0.005
20	α=0 ntip1 jpts9	visc-p1	20	9	1	-2.923	0.000	2.923	0.000	0.312	0.000	0.005	0.005
21	α=0 ntip2 jpts9 (d)	visc-p1	20	9	2	-2.923	0.000	2.923	0.000	0.309	0.000	0.005	0.006
22	α=0 ntip2 jpts1	visc-p1	20	1	2	-2.923	0.000	2.923	0.000	0.309	0.000	0.005	0.006
23	α=0 ntip0 ipts80 (a)	visc-p1	80	9	0	-2.923	0.000	2.923	0.000	0.318	0.000	0.005	0.005
24	α=0 ntip1 ipts80 (b)	visc-p1	80	9	1	-2.923	0.000	2.923	0.000	0.319	0.000	0.005	0.005
25	α=0 ntip2 ipts80 (c)	visc-p1	80	9	2	-2.923	0.000	2.923	0.000	0.317	0.000	0.005	0.005
26	α=0 ntip2 jpts1	visc-p1	80	1	2	-2.923	0.000	2.923	0.000	0.317	0.000	0.005	0.005
27	α=6 ntip0 ipts80 (a)	visc-p1	80	9	0	-2.923	6.000	8.923	6.000	0.969	0.001	0.007	0.008
28	α=6 ntip1 ipts80 (b)	visc-p1	80	9	1	-2.923	6.000	8.923	6.000	0.967	0.001	0.007	0.008
29	α=6 ntip2 ipts80 (c)	visc-p1	80	9	2	-2.923	6.000	8.923	6.000	0.965	0.002	0.007	0.008
30	α=6 ntip2 jpts9 (d)	visc-p1	20	9	2	-2.923	6.000	8.923	6.000	0.940	0.004	0.007	0.011
31	α=0 αzl=p7	visc-p7	20	9	2	-8.996	0.000	8.996	0.000	0.977	0.001	0.007	0.008
32	α=-8.996 αzl=p7	visc-p7	20	9	2	-8.996	-8.996	0.000	-8.996	0.000	0.000	0.006	0.006

Are the relative section incidence angle differences modeled properly?

Changing the incidence angle of the *p0* airfoil produces nearly identical changes to the section αzl. The differences at higher angles of attack are attributable to effects of the cosine function on c_{ref} and C_l.

If various combinations of the wing-α and the associated airfoil-αzl can be summed to yield identical effective angles of attack, are the 3d-aerodynamic results identical?

Numerous combinations of these parameters are shown in Table 30, and all cases produce consistent aerodynamics output. For example, Case 6 and Case 17 can be directly compared to determine that the airfoil C_l and C_d closely match the wing C_L and C_D. In general, the integrated lift is a lesser value for the wing than for the airfoil. This is because the MVL-15 methodology does not include finite wing effects across all spanwise stations when calculating the integrated 2d-aerodynamics output. Rather, the integration is based on the 2d-aerodynamic properties at the root chord station. Note that this 2d-analysis methodology applies to only the integrated aerodynamics listed in the *out_aero.txt* file, and that values listed in the *out_span.txt* file are not modified.

If the aerodynamic results depend on the lattice input parameter values, is the dependency reasonable within the context of the modeling scope?

The variation of the integrated aerodynamics results with lattice input parameters is minimal. For these 3d-analyses, the variations can be further reduced by increasing the number of spanwise lattice points and decreasing the number of allowable wing-tip convergence points. At some point, for more complex planforms, it becomes necessary to increase the value of the wing-tip input parameter to improve, or enable, convergence.

Do the 3d-analysis results reflect the properties listed in the 2d-aerodynamics tables?

All cases indicate that the 3d-inviscid solutions are properly matched to the 2d-aerodynamics. Case 32 can be compared to Case 8 to demonstrate that even for higher angles of attack, the linking methodology remains consistent. The differences between Case 31 and Case 32 indicate that the 2d-aerodynamics table associated with Case 8 was accessed at different wing section angles of attack. This can be confirmed by assessing the *p7* aerodynamics plots of C_D vs. C_L and C_L vs. α, as shown in Figure 6, Section 8.1.

8.3 Airfoil and Wing Aerodynamics: Varying the Wing Geometry and 2d-Properties

After the basic validations described in Section 8.2 had been completed, the analysis progressed to include more variations of the 3d-wing parameters. The 3d-validation cases presented in this section are based on varying the nominal AR=1000 rectangular wing (co=1.0, b/2=500.0) to investigate the effects of changing the chord length, the flap chord, the number of wing panels, and the lift curve augmentation parameter. There are two groups of validation cases; the first group represents a modest extension of the previous validation cases, whereas the second group includes a variety of challenging cases that engage new aspects of the MVL-15 methodology. The results of the first group of validation cases are listed in Table 31, and the results of the second group of validation cases are listed in Table 32. Visualizing the wing geometry variations listed in these tables is simplified by referring to the schematic illustrations shown in Figure 12 (Table 31) and Figure 14 (Table 32). The spanwise lift distributions that were summed to calculate the integrated aerodynamic validation results are shown in Figure 13 (Table 31) and Figure 15 (Table 32).

In Table 31, the 2d-analyses are listed as validation Cases 1-2, and the 3d-analyses are listed as validation Cases 3-10. There are four pairs of 3d-validation cases; a distinct geometry model associated with each validation case was analyzed at α=0.0 degrees and α=2.9232 degrees. The geometry models include the nominal case, the nominal case using two wing panels with identical airfoil sections, and two c_{fxr}=2.0 cases: one with c_o=2.0 c_{fx}=1.0, and the other with c_o=1.0 c_{fx}=2.0. As the δ_f=0.0 degrees for these cases, the resultant extended flap chord, c_{fxr}, is equivalent to the projection of the extended flap chord, $c_{fp.}$ To test the consistency within pairs, the odd-numbered cases were evaluated at α=0.0 degrees, and were associated with a 2d-section αzl=2.9232 degrees; the even-numbered cases were evaluated at α=2.9232 degrees, and were associated with a 2d-section αzl=0.0 degrees. All four pairs are shown to provide consistent results. This indicates that the effective angle of attack for both elements of the pair are equivalent, despite having been specified by two separate approaches.

Comparing the results of Cases 3-4 with Cases 5-6 indicates that modeling the wing as either one or two panels yields identical results. The comparison validates that multiple wing panels can be input via the *in_2d-geom.txt*, *in_2d-aero.txt*, and *in_wing1x.txt* input files, and then accessed, analyzed, and output by MVL-15. This critical step allows application to more complicated wing planform geometry.

Cases 7-10 provide the first examples that the integrated aerodynamic results depend on the *S1 nofl* and *S1 flap* reference areas. For these cases, the resultant flap chord lengths (i.e., c_{fxr}=2.0) are twice those of Cases 3-6 (i.e., c_{fxr}=1.0), and the finite-wing effects remain small (AR=500, b/2=500.0). Thus, the bound circulation – a measure of the lifting force – of Cases 7-10 is approximately twice that of Cases 3-6. The bound circulation output, Gm/Sk (Table 14, file: *out_aero.txt*), is listed for each of the separate wings of the analysis. Cases 7-8 demonstrate that doubling the wing nominal chord (i.e., c_o=c_{fxr}=2.0) produces integrated aerodynamic coefficients that are nearly equivalent to those of Cases 1-4; the minor differences are attributable to finite wing effects (AR=1000 vs. AR=500). Cases 9-10 demonstrate that doubling the wing chord by extending flaps (i.e., c_o=1, c_{fx}=c_{fxr}=2.0) produces both the previously described integrated aerodynamic coefficients and a set of coefficients based on the nominal wing reference area without flaps.

For any aerodynamics analysis, it is important to ensure that the reference parameters are defined and applied consistently. When implementing the modified vortex-lattice methodology, additional accounting is required to ensure that the 2d-aerodynamics tables are properly associated with variations of the wing geometry. For example, linking the wing chord of Cases 7-8 must be executed differently than linking the wing chord of Cases 9-10. This becomes especially important when analyzing abrupt changes in the spanwise lift and induced angles of attack. The results described in Cases 7-10 indicate that these parameters are properly considered, manipulated, and analyzed.

Table 31. Airfoil and Wing Aerodynamics: Varying the Section Properties, c_o, c_f, and *npanels*

Case	Geometry 2d-name	Aero 2d-name	Section δsi	Section α-2d	Effective 2d α	OUTPUT > aero ref	S_wing	2d "AR"	2d αzl	CL Σ c Cl dy	CD-ind	Cdf-2d	CD-tot
1	visc-f0	aero-0	0.0	0.0	0.0	**wing1**	1000.0	1000.0	0.0000	0.0000	0.0000	0.0051	0.0051
2	visc-f29	aero-29	2.9232	0.0	2.9232	**wing1**	1000.0	1000.0	0.0000	0.3208	0.0000	0.0061	0.0061
Case	**Geometry panel: co-cf-cla**	**Aero 2d-name**	**Section 2d αzl**	**Wing α-3d**	**Effective 3d α**	**OUTPUT > aero ref**	**S_wing**	**Gm/Sk AR**	**α, deg**	**CL Σ c Cl dy**	**CD-ind**	**Cdf-2d**	**CD-tot**
3	panel 1: 1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	1000.0	318.7	0.0000	0.3187	0.0001	0.0051	0.0052
						S1 flap	1000.0	1000.0	0.0000	0.3187	0.0001	0.0051	0.0052
						S1 nofl	1000.0	1000.0	0.0000	0.3187	0.0001	0.0051	0.0052
4	panel 1: 1-1-1	aero-0	0.0	2.9232	2.9232	**wing 1**	1000.0	318.3	2.9230	0.3183	0.0001	0.0051	0.0052
						S1 flap	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
						S1 nofl	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
5	panel 1: 1-1-1 panel 2: 1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	1000.0	318.7	0.0000	0.3187	0.0001	0.0051	0.0052
						S1 flap	1000.0	1000.0	0.0000	0.3187	0.0001	0.0051	0.0052
						S1 nofl	1000.0	1000.0	0.0000	0.3187	0.0001	0.0051	0.0052
6	panel 1: 1-1-1 panel 2: 1-1-1	aero-0	0.0	2.9232	2.9232	**wing 1**	1000.0	318.3	2.9230	0.3183	0.0001	0.0051	0.0052
						S1 flap	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
						S1 nofl	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
7	panel 1: 2-1-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	2000.0	635.6	0.0000	0.3178	0.0001	0.0051	0.0052
						S1 flap	2000.0	500.0	0.0000	0.3178	0.0001	0.0051	0.0052
						S1 nofl	2000.0	500.0	0.0000	0.3178	0.0001	0.0051	0.0052
8	panel 1: 2-1-1	aero-0	0.0	2.9232	2.9232	**wing 1**	2000.0	634.9	2.9230	0.3174	0.0001	0.0051	0.0053
						S1 flap	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
						S1 nofl	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
9	panel 1: 1-2-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	2000.0	635.6	0.0000	0.3178	0.0001	0.0051	0.0052
						S1 flap	2000.0	500.0	0.0000	0.3178	0.0001	0.0051	0.0052
						S1 nofl	1000.0	1000.0	0.0000	0.6356	0.0002	0.0102	0.0104
10	panel 1: 1-2-1	aero-0	0.0	2.9232	2.9232	**wing 1**	2000.0	634.8	2.9230	0.3174	0.0001	0.0051	0.0053
						S1 flap	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
						S1 nofl	1000.0	1000.0	2.9230	0.6348	0.0003	0.0102	0.0105

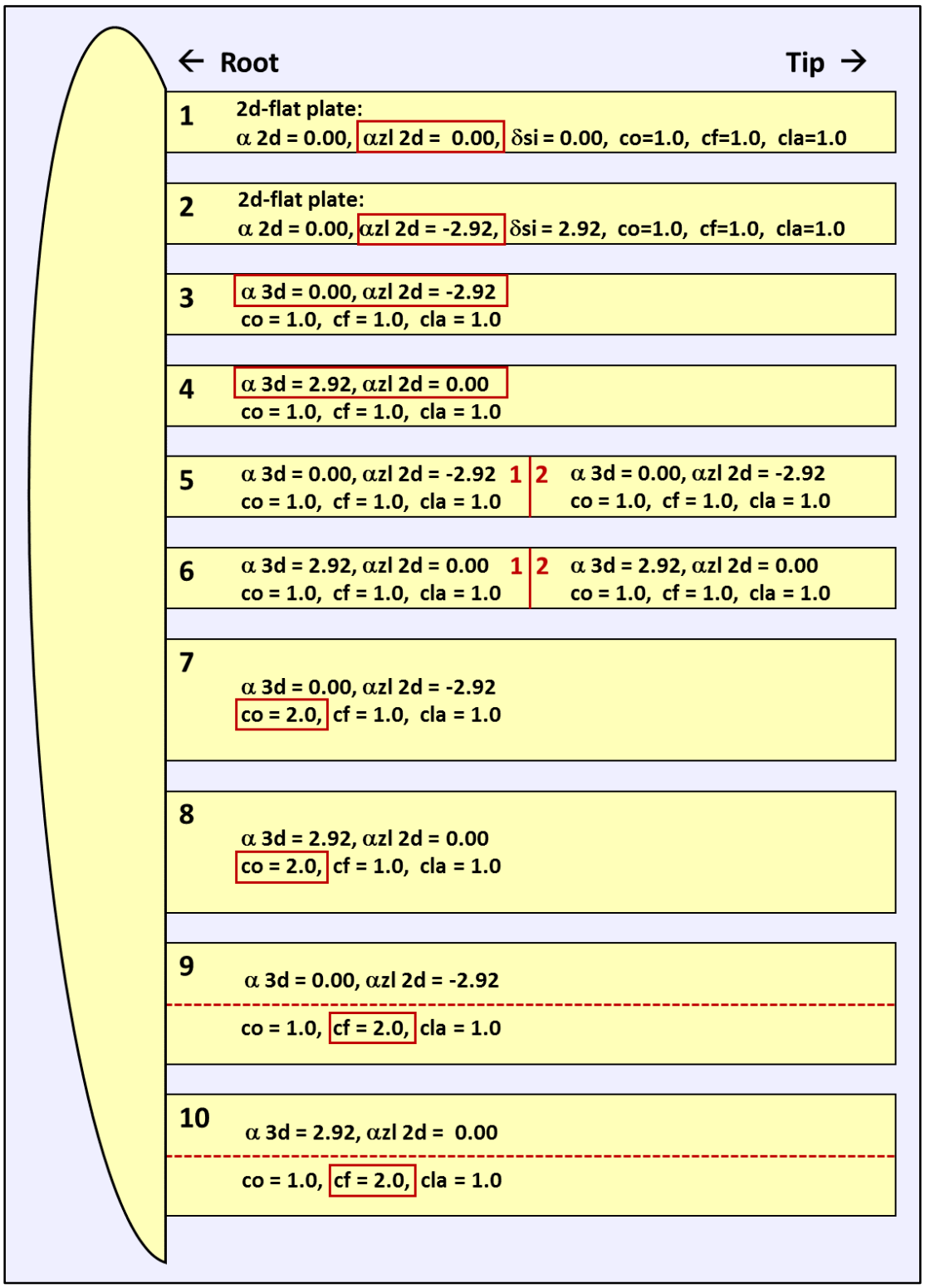


Figure 12. Geometry illustration for the validation cases listed in Table 31.

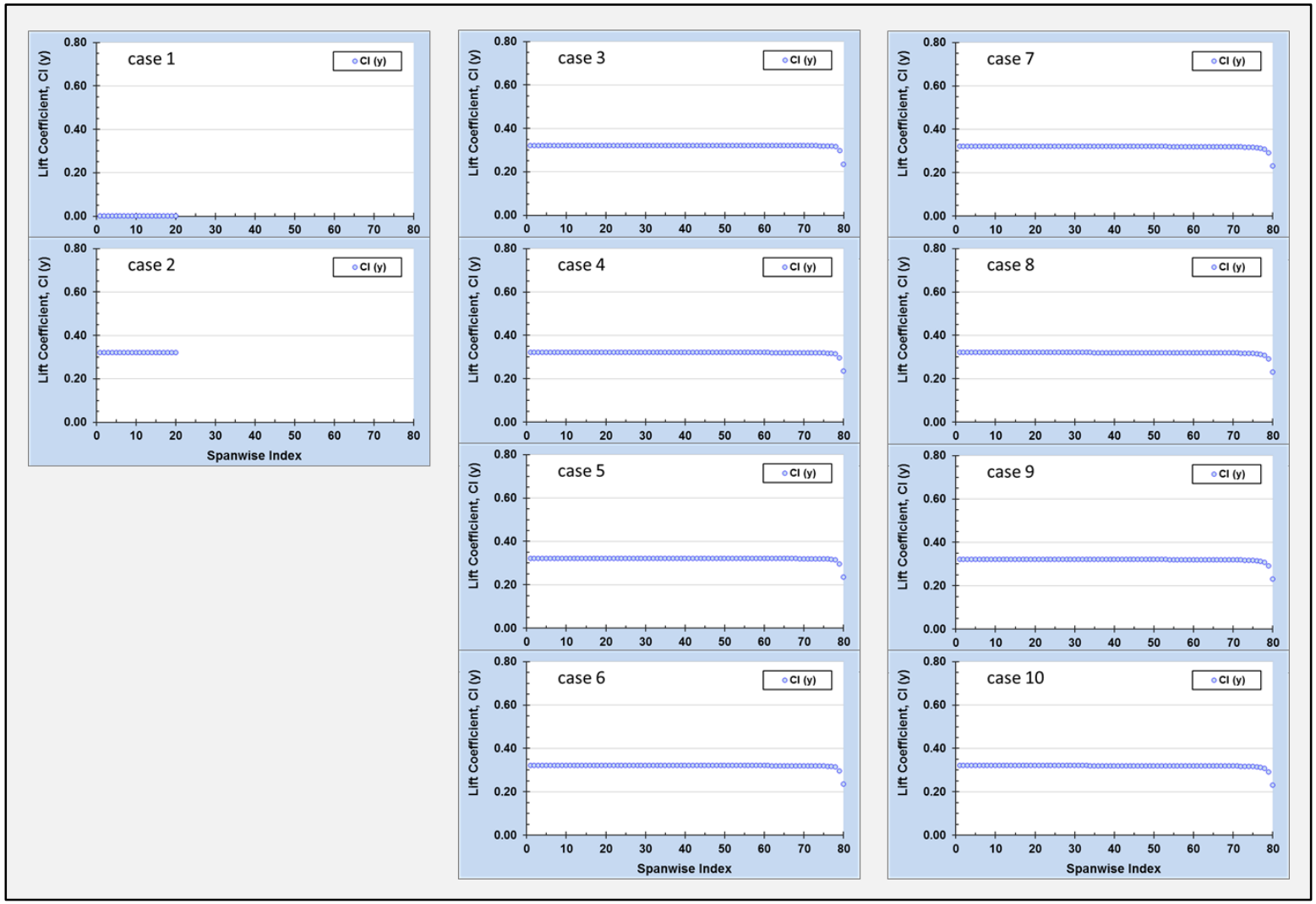


Figure 13. Spanwise lift for the validation cases listed in Table 31.

The second group of 3d-validation cases is shown in Table 32; unique variations and features of the validation cases are indicated by red outlines and brief notations to facilitate comparisons. Similar to the even-numbered cases of Table 31, all of these cases were evaluated at α=2.9232 degrees, and were associated with a 2d-section αzl=0.0 degrees. The nominal AR=1000 wing was modeled using two panels and was modified to create the distinct geometry of each validation case.

The validation cases of this section were developed to eliminate the uniformity resulting from the use of the rectangular wing planform that was required to assess the results consistency presented in Table 30 and Table 31. Additionally, the wing lift-curve augmentation parameter was analyzed in Cases 4-6 and Case 12. Many of these validation cases feature an additional row of output based on the *Swaero* (file: *in_wing1x.txt*) reference area. The results of Table 32 should be interpreted in a similar manner as those in Table 31. The wing geometry is significantly more complicated, yet the results remain consistent and predictable. This strengthens the previous assessment that the parameters of interest are properly considered, manipulated, and analyzed.

The lift coefficient results obtained by using alternate approaches to set up the analysis are shown in Table 33. For validation Cases 1-16, α=0.0 degrees and αzl=-2.9232 degrees; for validation Cases 17-32, α=0.0 degrees and αzl=-2.9232 degrees. Four separate cases were created by varying the values of the input parameters, *cflap* and *2dratio* (file: *in_wing1x.txt*) to specify lift augmentation via the 3d-input options. The variations associated with each case are highlighted in green. Each case was complemented by four separate cases that were set up to specify lift augmentation according to the values specified in the 2d-aerodynamics tables. All combinations of the four input parameter cases and 2d-aerodynamics cases were analyzed for both combinations of α and αzl. The results of all cases were compared to determine if the various factors combined, either separately or in tandem, to produce the intended effects on the lift coefficient. The complete assessment of the results indicates that although the analyses were approached from differing perspectives, equivalent lift coefficient changes were obtained.

Table 32. Aerodynamics of a Wing with Two Panels: Varying c_o, c_f, and $C_{l\alpha}$

Case	Geometry panel: co-cf-cla	Aero 2d-name	Section 2d αzl	Wing α-3d	Effective 3d α	OUTPUT > aero ref	S_wing	Gm/Sk AR	α, deg	CL Σ c Cl dy	CD-ind	Cdf-2d	CD-tot
1	panel 1: 1-1-1	aero-0	0.0000	2.9232	2.9232	wing 1	1000.0	318.3	2.9230	0.3183	0.0001	0.0051	0.0052
	2y/b= 0.0 to 0.5					wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
	panel 2: 1-1-1	aero-0	0.0000	2.9232	2.9232	S1 flap	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
	2y/b= 0.5 to 1.0					S1 nofl	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
					Nominal Case	Sw aero							
2	panel 1: 1-1-1	aero-0	0.0000	2.9232	2.9232	wing 1	753.1	240.2	2.9230	0.3189	0.0001	0.0051	0.0052
	panel 2: 0.5-1-1	aero-0	0.0000	2.9232	2.9232	wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	753.1	1327.8	2.9230	0.3189	0.0001	0.0051	0.0052
			Δco (panel 1 to panel 2) / (Δ2y/b): ΔS1 = +3.1			S1 nofl	753.1	1327.8	2.9230	0.3189	0.0001	0.0051	0.0052
						Sw aero							
3	panel 1: 1-1-1	aero-0	0.0000	2.9232	2.9232	wing 1	1000.0	318.3	2.9230	0.3183	0.0001	0.0051	0.0052
	panel 2: 0.5-2-1	aero-0	0.0000	2.9232	2.9232	wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
			Δcflap (panel 1 to panel 2) / (Δ2y/b): ΔS1 = 0.0			S1 nofl	750.0	1333.3	2.9230	0.4244	0.0001	0.0068	0.0070
						Sw aero							
4	panel 1: 1-1-2	aero-0	0.0000	2.9232	2.9232	wing 1	1000.0	478.3	2.9230	0.4783	0.0001	0.0051	0.0052
	panel 2: 1-1-1	aero-0	0.0000	2.9232	2.9232	wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1000.0	1000.0	2.9230	0.4783	0.0001	0.0051	0.0052
			cla 2x (panel 1) increases lift 50%			S1 nofl	1000.0	1000.0	2.9230	0.4783	0.0001	0.0051	0.0052
						Sw aero							
5	panel 1: 1-1-2	aero-0	0.0000	2.9232	2.9232	wing 1	1000.0	478.3	2.9230	0.4783	0.0001	0.0051	0.0052
	panel 2: 1-1-1	aero-0	0.0000	2.9232	2.9232	wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1000.0	1000.0	2.9230	0.4783	0.0001	0.0051	0.0052
			cla 2x (panel 1) increases lift 50%			S1 nofl	1000.0	1000.0	2.9230	0.4783	0.0001	0.0051	0.0052
			Compare: CL (Swaero) vs nominal CL (S1 nofl)			Sw aero	1500.0	666.7	2.9230	0.3189	0.0001	0.0034	0.0035
6	panel 1: 1-1-2	aero-0	0.0000	2.9232	2.9232	wing 1	1000.0	636.6	2.9230	0.6366	0.0002	0.0051	0.0053
	panel 2: 1-1-2	aero-0	0.0000	2.9232	2.9232	wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1000.0	1000.0	2.9230	0.6366	0.0002	0.0051	0.0053
			cla 2x (panels 1 & 2) increases lift 100%			S1 nofl	1000.0	1000.0	2.9230	0.6366	0.0002	0.0051	0.0053
						Sw aero							
7	panel 1: 1-2-1	aero-0	0.0000	2.9232	2.9232	wing 1	1506.3	479.3	2.9230	0.3182	0.0001	0.0051	0.0052
	panel 2: 1-1-1	aero-0	0.0000	2.9232	2.9232	wing 2	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1506.3	663.9	2.9230	0.3182	0.0001	0.0051	0.0052
			Δcflap (panel 1) / (Δ2y/b): ΔS1 = +6.3			S1 nofl	1006.3	993.8	2.9230	0.4763	0.0002	0.0077	0.0078
						Sw aero							

Table 32. Aerodynamics of a Wing with Two Panels: Varying c_o, c_f, and $C_{l\alpha}$ (continued)

Case	3d-Geometry panel: co-cf-cla	Aero 2d-name	Section 2d αzl	Wing α-3d	Effective 3d α	OUTPUT > aero ref	S_wing	Gm/Sk AR	α, deg	CL Σ c Cl dy	CD-ind	Cdf-2d	CD-tot
8	panel 1: 1-2-1	aero-0	0.0000	2.9232	2.9232	**wing 1**	1506.3	479.3	2.9230	0.3182	0.0001	0.0051	0.0052
	panel 2: 1-1-1	aero-0	0.0000	2.9232	2.9232	**wing 2**	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1506.3	663.9	2.9230	0.3182	0.0001	0.0051	0.0052
			Δcflap (panel 1) / (Δ2y/b): ΔS1 = +6.3			**S1 nofl**	1006.3	993.8	2.9230	0.4763	0.0002	0.0077	0.0078
			Compare: CL (Swaero) vs nominal CL (S1 nofl)			**Sw aero**	1500.0	997.9	2.9230	0.3196	0.0001	0.0051	0.0052
9	panel 1: 1-2-1	aero-0	0.0000	2.9232	2.9232	**wing 1**	2000	634.8	2.9230	0.3174	0.0001	0.0051	0.0053
	panel 2: 1-2-1	aero-0	0.0000	2.9232	2.9232	**wing 2**	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
						S1 nofl	1000.0	1000.0	2.9230	0.6348	0.0003	0.0102	0.0105
			Compare: CL (Swaero) vs nominal CL (S1 nofl)			**Sw aero**	2000.0	1000.0	2.9230	0.3174	0.0001	0.0051	0.0053
10	panel 1: 2-1-1	aero-0	0.0000	2.9232	2.9232	**wing 1**	2000.0	634.8	2.9230	0.3174	0.0001	0.0051	0.0053
	panel 2: 2-1-1	aero-0	0.0000	2.9232	2.9232	**wing 2**	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
						S1 nofl	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
			Compare: CL (Swaero) vs nominal CL (S1 nofl)			**Sw aero**	2000.0	500.0	2.9230	0.3174	0.0001	0.0051	0.0053
11	panel 1: 0.5-2-1	aero-0	0.0000	2.9232	2.9232	**wing 1**	1000	318.3	2.9230	0.3183	0.0001	0.0051	0.0052
	panel 2: 0.5-2-1	aero-0	0.0000	2.9232	2.9232	**wing 2**	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1000.0	1000.0	2.9230	0.3183	0.0001	0.0051	0.0052
						S1 nofl	500.0	2000.0	2.9230	0.6366	0.0002	0.0102	0.0104
			Compare: CL (Swaero) vs nominal CL (S1 nofl)			**Sw aero**	1000.0	2000.0	2.9230	0.3183	0.0001	0.0051	0.0052
12	panel 1: 1-1-1.5	aero-0	0.0000	2.9232	2.9232	**wing 1**	1000.0	477.4	2.9230	0.4774	0.0002	0.0051	0.0053
	panel 2: 1-1-1.5	aero-0	0.0000	2.9232	2.9232	**wing 2**	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1000.0	1000.0	2.9230	0.4774	0.0002	0.0051	0.0053
			cla 1.5x on panels 1&2 increases lift 50%			**S1 nofl**	1000.0	1000.0	2.9230	0.4774	0.0002	0.0051	0.0053
			Compare: CL (Swaero) vs nominal CL (S1 nofl)			**Sw aero**	1500.0	666.7	2.9230	0.3183	0.0001	0.0034	0.0035
13	panel 1: 1-1.5-1	aero-0	0.0000	2.9232	2.9232	**wing 1**	1500	476.8	2.9230	0.3179	0.0001	0.0051	0.0052
	panel 2: 1-1.5-1	aero-0	0.0000	2.9232	2.9232	**wing 2**	0.0	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
						S1 flap	1500.0	666.7	2.9230	0.3179	0.0001	0.0051	0.0052
						S1 nofl	1000.0	1000.0	2.9230	0.4768	0.0002	0.0077	0.0079
			Case 12 vs Case 13: Compare CL and reference areas			**Sw aero**	1500.0	1000.0	2.9230	0.3179	0.0001	0.0051	0.0052

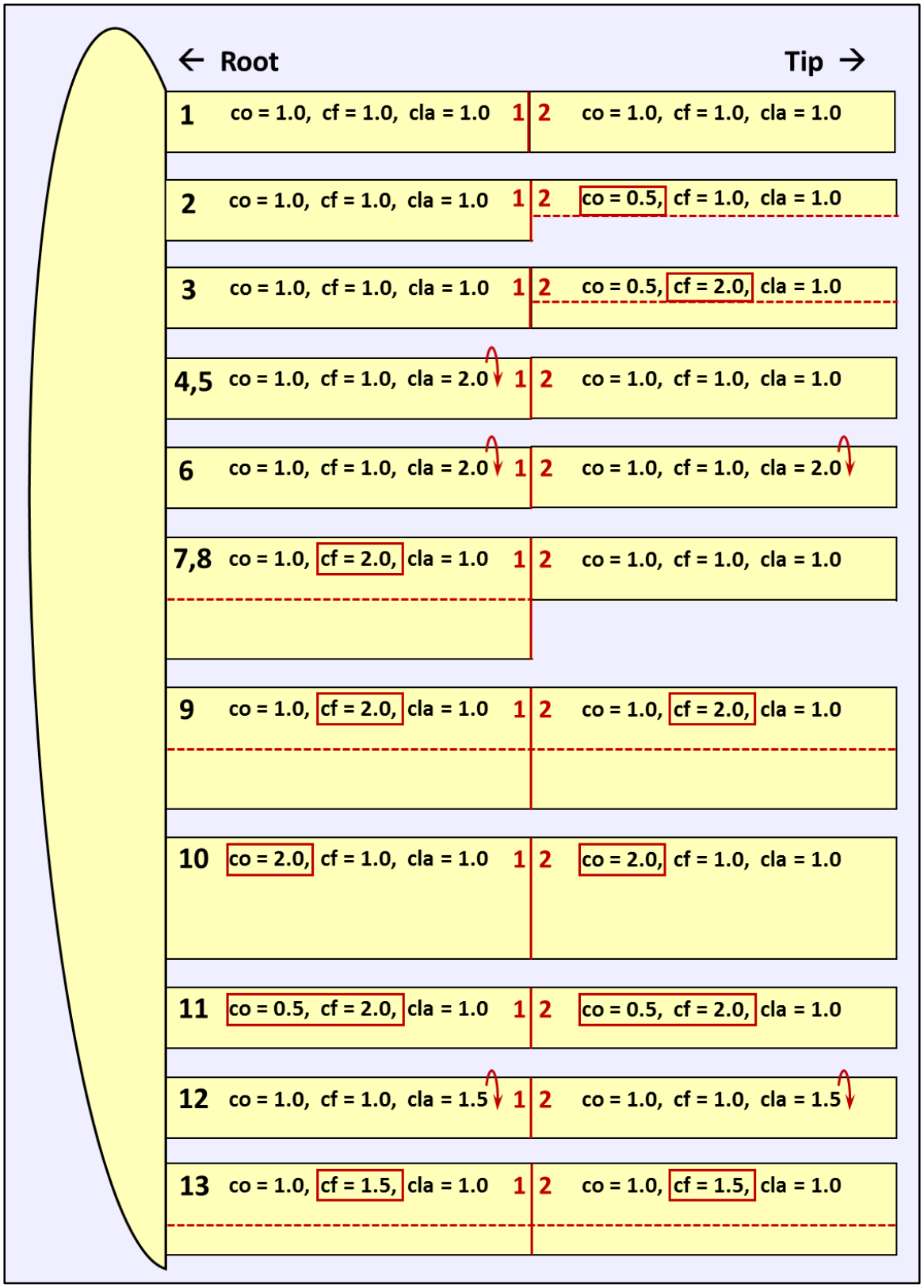


Figure 14. Geometry illustration for the validation cases listed in Table 32.

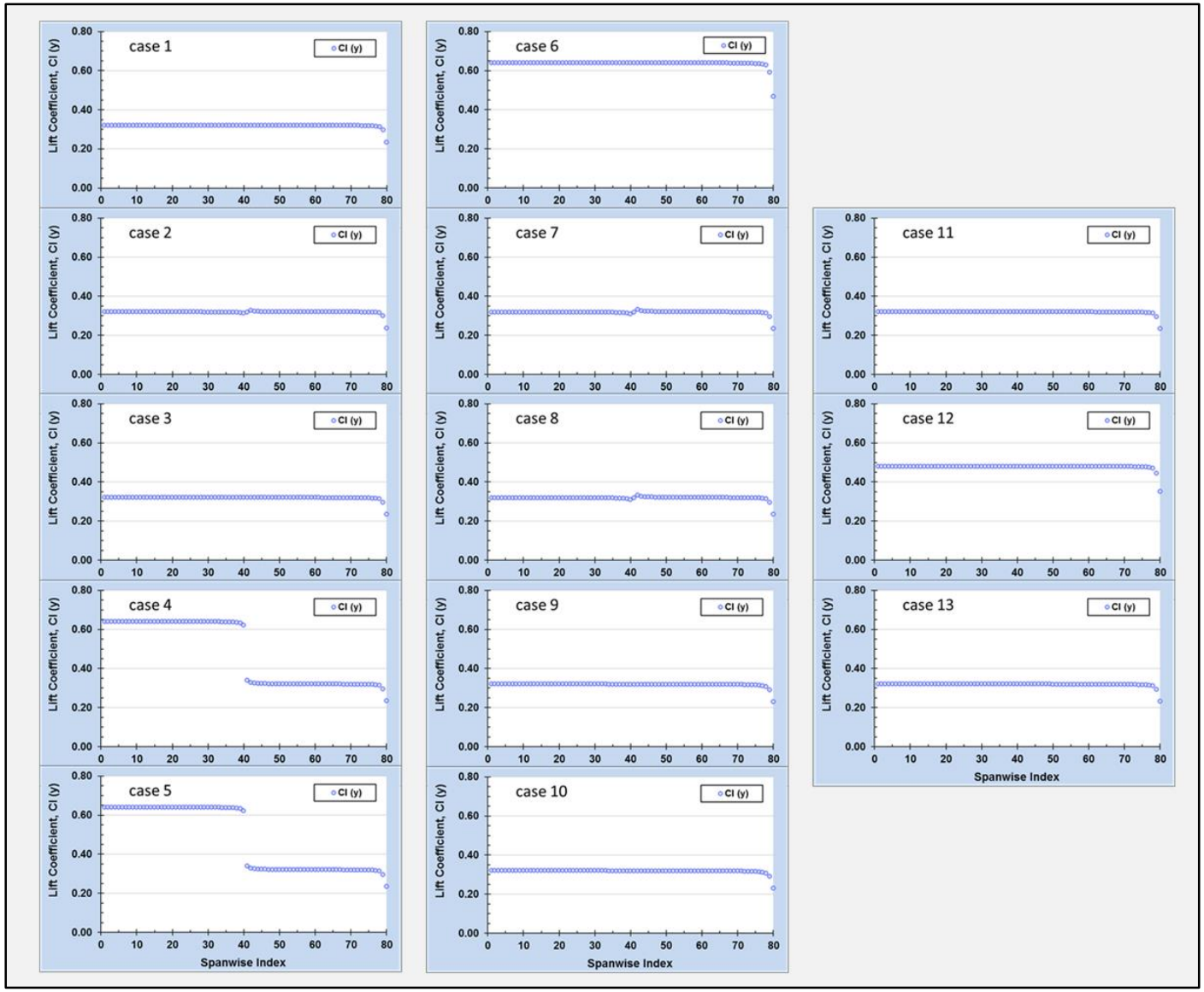


Figure 15. Spanwise lift for the validation cases listed in Table 32.

Table 33. Alternate Analysis Strategies: Lift Coefficient Results Comparison

3d-Input	Output S ref, C_L	2d-aero: $\alpha z l$ =-2.923 Clα=1.0	2d-aero: $\alpha z l$ =-2.923 Clα=1.5	2d-aero: $\alpha z l$ =-2.923 Clα=2.0	2d-aero: $\alpha z l$ =-2.923 Clα=2.25
α=0.0		**Case 1**	**Case 2**	**Case 3**	**Case 4**
Clα=1.0	S1 flap, C_L	0.3172	0.4758	0.6344	0.7138
cflap=1.0	S1 nofl, C_L	0.3172	0.4758	0.6344	0.7138
α=0.0		**Case 5**	**Case 6**	**Case 7**	**Case 8**
Clα=1.5	S1 flap, C_L	0.4758	0.7138	0.9517	1.0706
cflap=1.0	S1 nofl, C_L	0.4758	0.7138	0.9517	1.0706
α=0.0		**Case 9**	**Case 10**	**Case 11**	**Case 12**
Clα=1.0	S1 flap, C_L	0.3168	0.4752	0.6337	0.7129
cflap=1.5	S1 nofl, C_L	0.4752	0.7129	0.9505	1.0693
α=0.0		**Case 13**	**Case 14**	**Case 15**	**Case 16**
Clα=1.5	S1 flap, C_L	0.4752	0.7129	0.9505	1.0693
cflap=1.5	S1 nofl, C_L	0.7129	1.0693	1.4257	1.6039

3d-Input	Output S ref, C_L	2d-aero: $\alpha z l$ =0.0 Clα=1.0	2d-aero: $\alpha z l$ =0.0 Clα=1.5	2d-aero: $\alpha z l$ =0.0 Clα=2.0	2d-aero: $\alpha z l$ =0.0 Clα=2.25
α=2.923		**Case 17**	**Case 18**	**Case 19**	**Case 20**
Clα=1.0	S1 flap, C_L	0.3141	0.4711	0.6281	0.7066
cflap=1.0	S1 nofl, C_L	0.3141	0.4711	0.6281	0.7066
α=2.923		**Case 21**	**Case 22**	**Case 23**	**Case 24**
Clα=1.5	S1 flap, C_L	0.4711	0.7066	0.9421	1.0599
cflap=1.0	S1 nofl, C_L	0.4711	0.7066	0.9421	1.0599
α=2.923		**Case 25**	**Case 26**	**Case 27**	**Case 28**
Clα=1.0	S1 flap, C_L	0.3133	0.4700	0.6267	0.7050
cflap=1.5	S1 nofl, C_L	0.4700	0.7050	0.9400	1.0575
α=2.923		**Case 29**	**Case 30**	**Case 31**	**Case 32**
Clα=1.5	S1 flap, C_L	0.4700	0.7050	0.9400	1.0575
cflap=1.5	S1 nofl, C_L	0.7050	1.0575	1.4100	1.5862

8.4 Airfoil Flap Geometry and Aerodynamics

The MVL-15 2d-analysis methodology and validation results for airfoils with deployed flaps are described in this section, with reference to the information presented in Section 6.1.2 and Section 8.1-8.3.

The wing section geometry of the outboard takeoff flaps, shown previously in Figure 5 (Section 8.1) was based on the MVL-15 2d-analysis model output. Figure 16 facilitates a comparison of the same geometry output with the non-dimensional geometry of the *2d-Variants Utility* and the MVL-15 3d-analysis output. The comparison to the *2d-Variants Utility* geometry is direct, and there are no apparent differences. The comparison to the MVL-15 3d-analysis output requires two steps. The first is to ensure that the chordwise scaling remains consistent during the analysis by supplying the 2d non-dimensional factor, c_{fxr}, to the 3d-analysis via the input parameter, *cflap* (file: *in_wing1x.txt*). Neglecting the positioning of the lattice control points at the ¾-chord of each lattice element, Figure 16 shows there are no apparent chord length differences. Next, the modified vortex-lattice methodology requires that the aerodynamic influences due to the 2d-curvature of the wing section are replaced by the associated 2d-αzl and that the 3d-section geometry z-coordinates are set to 0.0. Consequently, the 3d-geometry and the 2d-geometry depicted in Figure 16 are consistent, when considered in tandem with the previously validated geometry-aerodynamics equivalence of Section 8.2 and Section 8.3.

A matrix of 2d-geometry variants was created utilizing a nominal airfoil and a wide range of deployed flap configurations to test the accuracy and trends of the MVL-15 2d-analysis results for αzl and $\Delta\alpha zl$. The retracted flap chord, extended flap chord, and the flap deflection angle were varied during the course of the testing; Table 34 summarizes the analysis result. The heading colors of the table help to visually differentiate analysis groups according to the flap extension factor, c_{fx}, and the light-blue highlighted analysis values of Table 34 are plotted in Figure 17. Empirical data was obtained from Reference 4 and is indicated in the figure. An approximate model of that airfoil geometry was developed and analyzed using MVL-15 at a flap deflection angle of 45 degrees and the flap parameters were assumed to be: c_{fr}=13% and c_{fx}=~1.9. Figure 17 shows that the 2d-analysis results and the overall trends show consistent and reasonable agreement with the empirical data from Reference 4. These trends indicate that MVL-15 is suitable for estimating the aerodynamics of airfoils with flaps, including: αzl, $\Delta\alpha zl$, $\Delta\alpha zl/\delta_f$, and C_l.

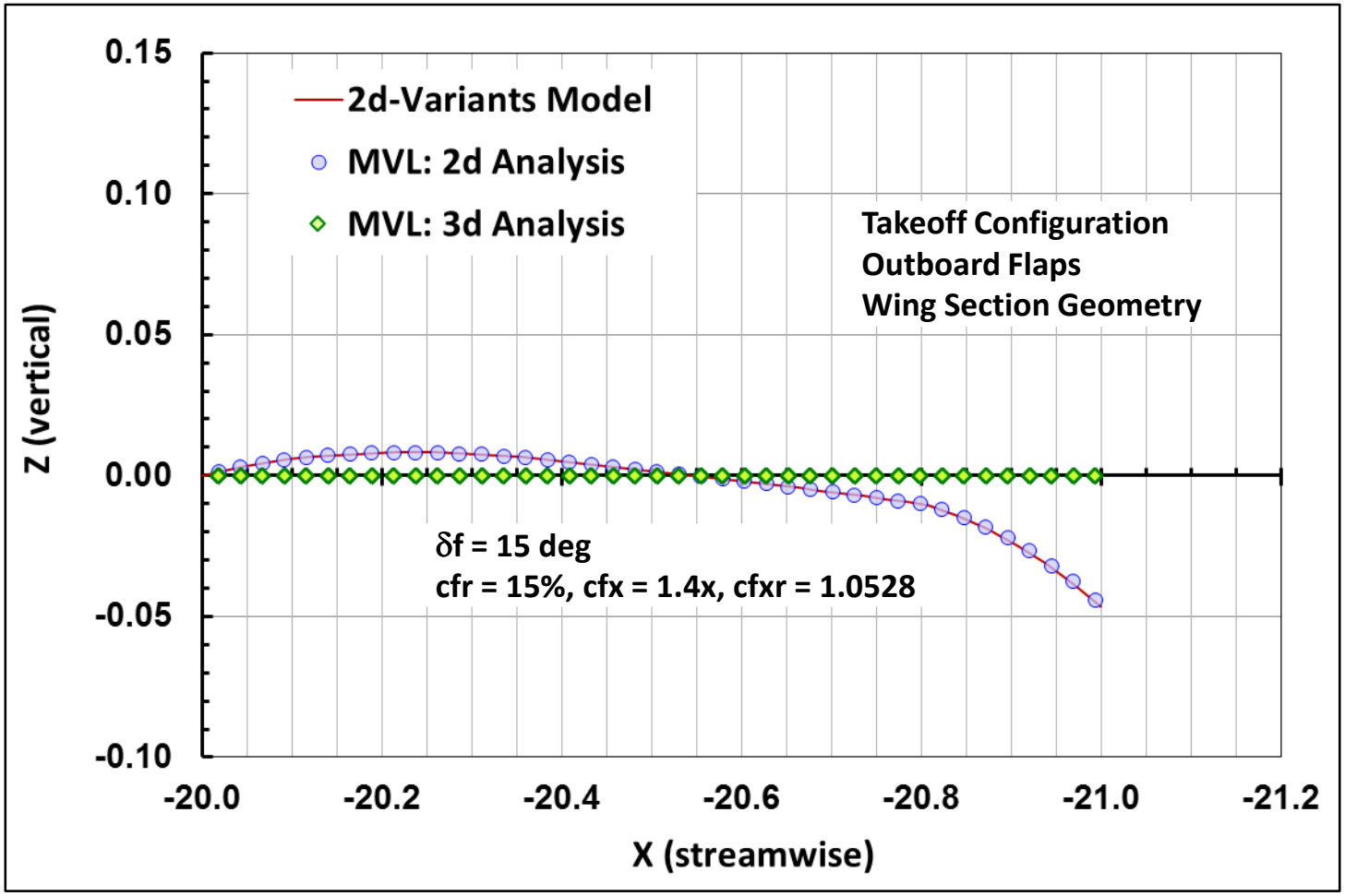


Figure 16. Airfoil geometry comparisons: 2d-Variants Utility, MVL-15 (2d), and MVL-15 (3d).

Table 34. Section Aerodynamic Results for Selected Flap Geometry Configurations

δ flap	cfr / co	cfx / cfr	1.2 x	MVL-15 2d		cfx / cfr	1.8 x	MVL-15 2d		cfx / cfr	2.4 x	MVL-15 2d	
		cfxr	Cl	$\alpha z\ell$	$\Delta \alpha z\ell$	cfxr	Cl	$\alpha z\ell$	$\Delta \alpha z\ell$	cfxr	Cl	$\alpha z\ell$	$\Delta \alpha z\ell$
10	**8%**	1.015	0.56	-5.07	-2.24	1.062	0.58	-5.27	-2.45	1.109	0.60	-5.45	-2.62
10	**12%**	1.022	0.63	-5.76	-2.94	1.093	0.65	-5.93	-3.10	1.164	0.67	-6.10	-3.27
10	**16%**	1.029	0.69	-6.31	-3.48	1.124	0.71	-6.44	-3.61	1.218	0.72	-6.58	-3.75
10	**20%**	1.036	0.74	-6.76	-3.93	1.155	0.75	-6.86	-4.03	1.273	0.77	-6.99	-4.16
20	**8%**	1.010	0.82	-7.50	-4.67	1.055	0.92	-8.37	-5.54	1.100	0.99	-9.07	-6.24
20	**12%**	1.015	0.99	-9.03	-6.20	1.083	1.09	-9.93	-7.10	1.151	1.17	-10.66	-7.83
20	**16%**	1.020	1.13	-10.26	-7.43	1.111	1.22	-11.16	-8.33	1.201	1.30	-11.89	-9.06
20	**20%**	1.026	1.24	-11.31	-8.48	1.138	1.34	-12.18	-9.36	1.251	1.42	-12.91	-10.08
30	**8%**	1.003	1.10	-10.07	-7.24	1.045	1.28	-11.68	-8.86	1.086	1.43	-13.05	-10.22
30	**12%**	1.005	1.40	-12.76	-9.93	1.067	1.59	-14.47	-11.65	1.129	1.75	-15.91	-13.08
30	**16%**	1.006	1.64	-14.95	-12.12	1.089	1.83	-16.70	-13.87	1.173	2.01	-18.29	-15.46
30	**20%**	1.008	1.84	-16.82	-13.99	1.112	2.04	-18.59	-15.76	1.216	2.23	-20.31	-17.48
40	**8%**												
40	**12%**	0.990	1.84	-16.79	-13.96								
40	**16%**	0.987	2.25	-20.53	-17.70								
40	**20%**	0.984	2.64	-24.05	-21.22								

δ flap	cfr / co	cfx / cfr	2.0 x	MVL-15 2d		cfx / cfr	2.5 x	MVL-15 2d		cfx / cfr	3.0 x	MVL-15 2d	
		cfxr	Cl	$\alpha z\ell$	$\Delta \alpha z\ell$	cfxr	Cl	$\alpha z\ell$	$\Delta \alpha z\ell$	cfxr	Cl	$\alpha z\ell$	$\Delta \alpha z\ell$
30	**16%**	1.117	1.89	-17.22	-14.39	1.186	2.02	-18.42	-15.59	1.256	2.13	-19.44	-16.61
40	**16%**	1.085	2.71	-24.74	-21.92	1.146	2.97	-27.12	-24.29	1.208	3.22	-29.35	-26.52
50	**16%**	1.046	3.60	-32.79	-29.96	1.097	4.11	-37.44	-34.61	1.149	4.53	-41.35	-38.52

δ flap	cfr / co	cfx / cfr	~1.9 x	(Reference 4)	
		cfxr	Cl ($\alpha z\ell$)	$\alpha z\ell$	$\Delta \alpha z\ell$
0	**~13%**	1.117	0.00	-1.84	0.00
10	**~13%**	1.113	0.68	-6.12	-4.29
20	**~13%**	1.102	1.22	-10.20	-8.37
35	**~13%**	1.072	2.05	-15.92	-14.08
45	**~13%**	1.045	2.49	-20.41	-18.57
45 MVL	**~13%**	1.045	2.55	-24.29	-22.45

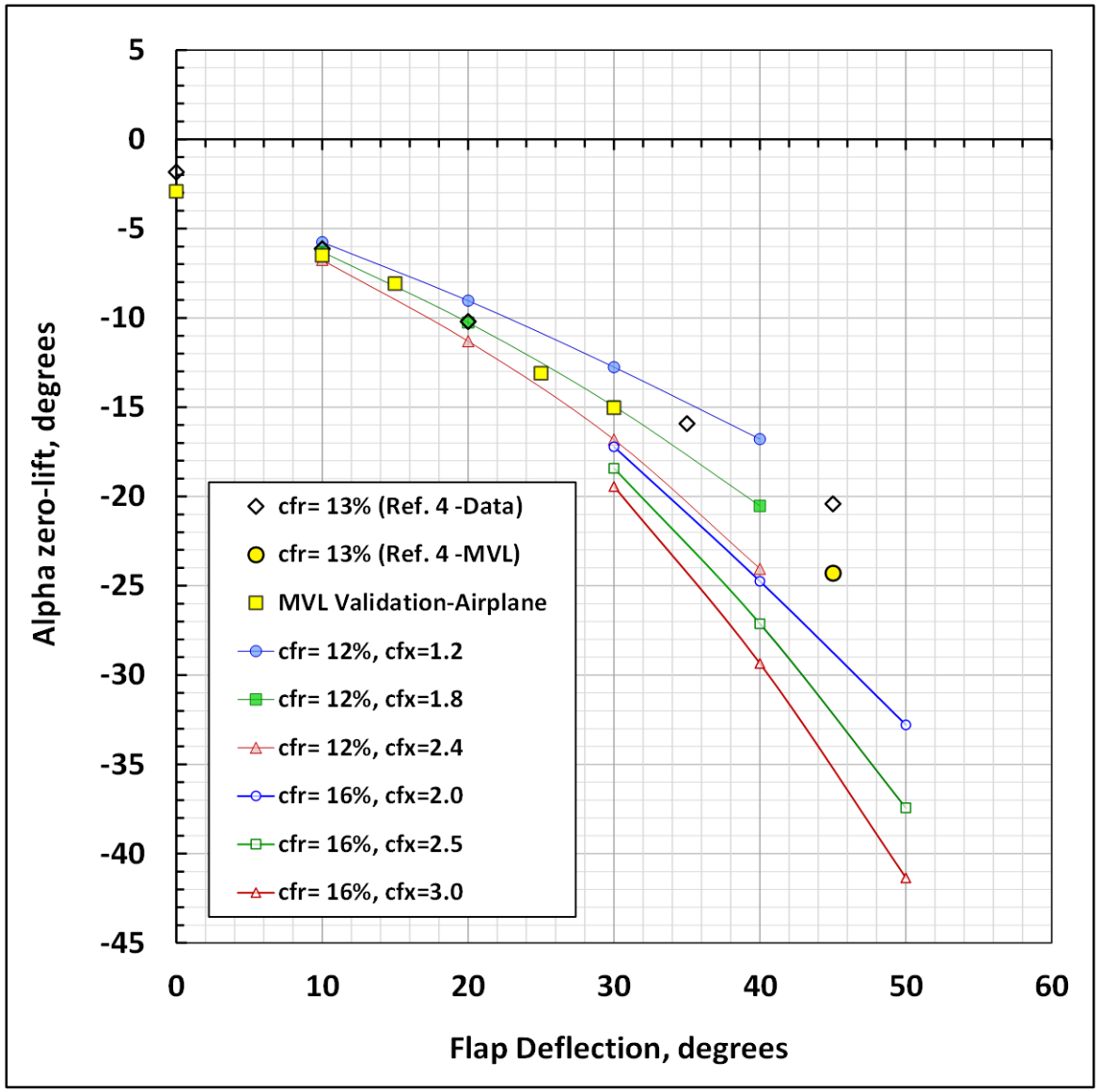


Figure 17. Airfoil flap $\Delta\alpha zl$ / δ_f, validation.

8.5 The 2d-Aerodynamics Adjustment Model

This section provides background information about the model development and application of the *shift* and *flap* adjustments. Figure 18 and Figure 19 provide information and analysis results for several airfoils with incidence angle and flap modifications, and summarizes how the 2d-aerodynamics adjustments can be implemented. Table 35 Figure 20 and provide information about the development of the *flaps* adjustment model, and the process of implementing these adjustments, when the section has been modified by flaps. The process reasonably transforms the characteristics of an empirically known airfoil as a practical analysis consideration, as unrestricted availability and access to the desired airfoil variations is unlikely. Note that the implementation of these two models is highly dependent on the capability to obtain the accurate and predictable 2d-analysis results demonstrated and described in the previous section.

Changes resulting from the *shift* adjustments model on the C_l vs. α lift-curve and on the C_d vs. C_l drag polar are shown in Figure 18. Consider, for example, the *p1* ($\delta si=+1$) geometry variant in which the zero-lift angle was modified according to the equation, $\alpha zl\ (p1)=\alpha zl\ (p0) - \delta si$. In this case, the intersection of the C_l vs. α curve with the x-axis appears shifted toward the –x direction, and the C_d vs. C_l drag polar appears to rotate clockwise about the minimum drag vertex.

Figure 19 illustrates that the vertex of the C_d vs. C_l drag polar appears to shift up and to the right, an indication of higher drag and higher lift, as the flap deflection angle increases. Note that for a given flap deflection angle, the right half of the associated C_d vs. C_l drag polar provides the best approximation to the data. This is a reasonable limitation because if operation at a lower C_l were desired, the flap deflection would be decreased, and the right half of that different C_d vs. C_l drag polar would become the best approximation to the data.

Figure 19 also illustrates changes resulting from the *flap* adjustments model on the C_l vs. α lift-curve that are similar to those described for the *shift* adjustments model. Although the first step in the process is to account for αzl, the changes resulting from the *flap* adjustments model are more complicated and require additional analysis steps. The *flap* adjustments model is based on trends developed from the analysis of empirical data obtained from Reference 4; the values associated with the analysis are shown in Table 35.

Figure 20 indicates the steps involved when adjusting the C_l vs. α curve utilizing the *flap* adjustments model. First, the nominal curve is shifted left by $\Delta\alpha zl$ due to the flap deployment (1). Next, separate corrections for $\Delta\alpha$ due to slats are applied at the low-C_l (2a) and high-C_l (2b) ends of the C_l vs. α curve to shift the curve to the right. Extending the α range as a result of slats permits the calculation of an adjusted C_{lmax}. However, a final empirical adjustment is necessary to account for $\Delta\alpha zl$ and $\Delta\alpha_{max}$ due to flaps and slats and involves applying separate corrections at the low-C_l (3a) and high-C_l (3b) ends of the C_l vs. α curve. The final position of the C_l vs. α curve is determined based on $\Delta\alpha zl$ (3a) and $\Delta\alpha_{max}$ (3b); note this final adjustment changes the lift curve slope.

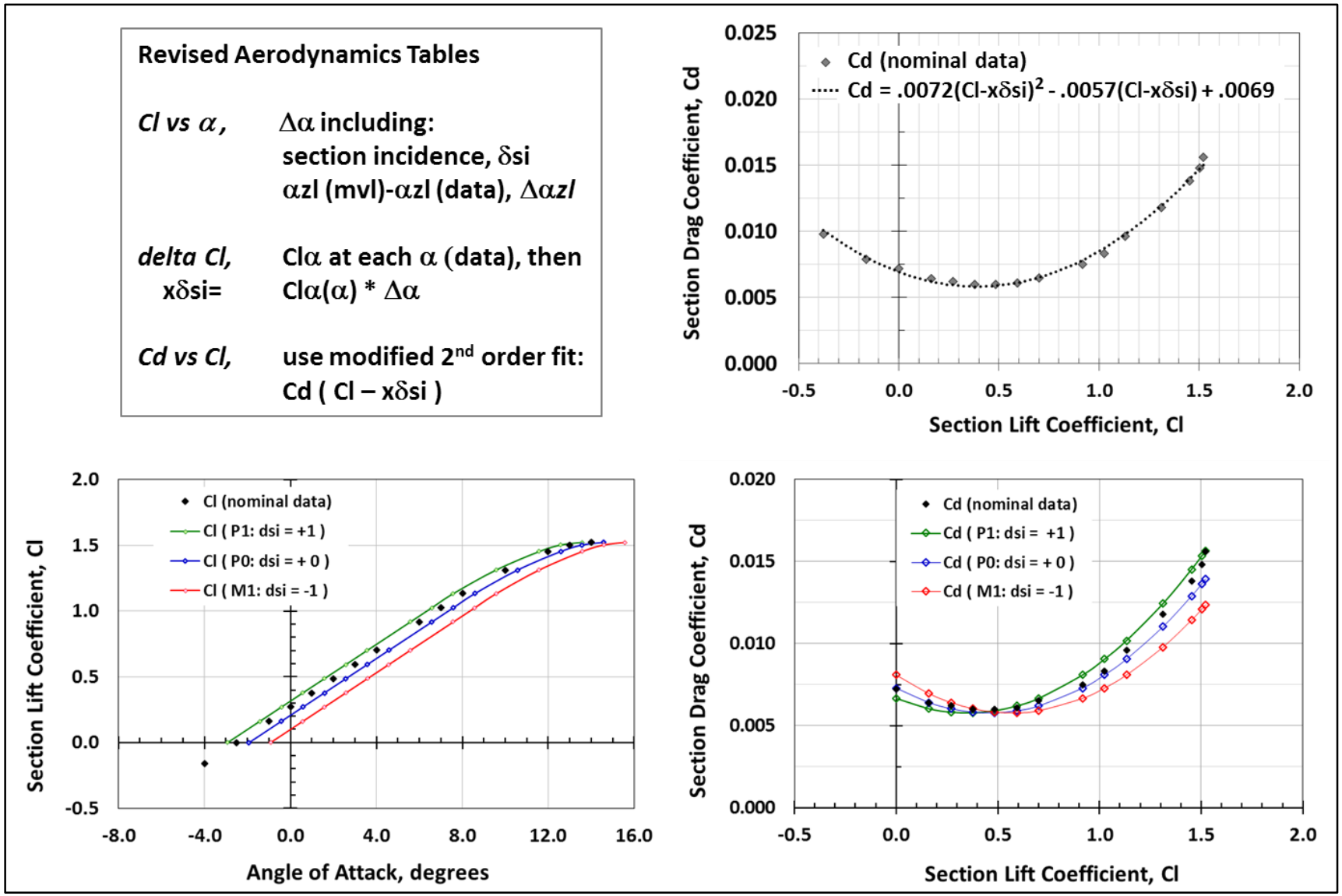


Figure 18. Airfoil aerodynamics model, incidence angle modifications.

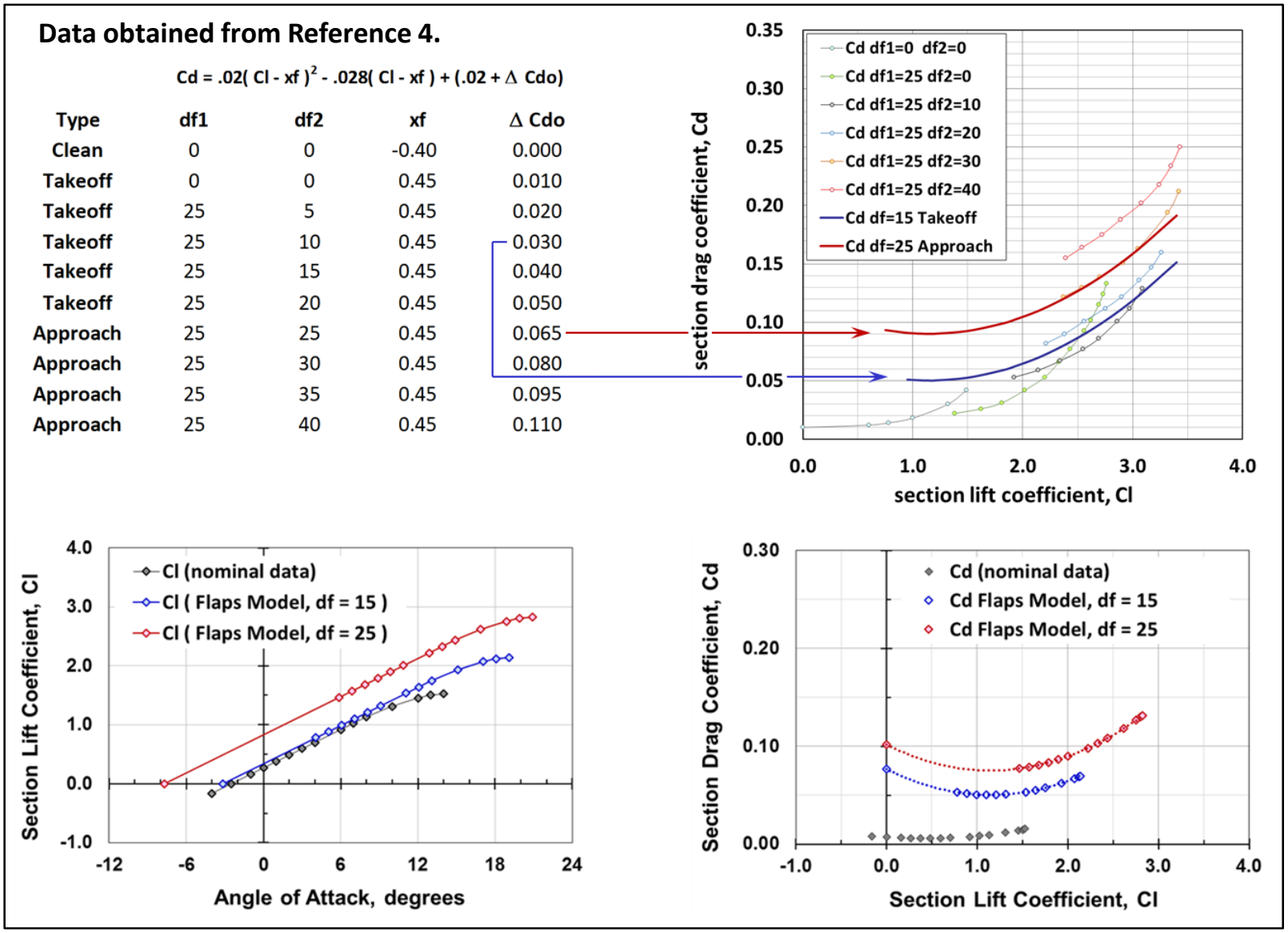


Figure 19. Airfoil aerodynamics model, flap modifications.

Table 35. Section Aerodynamics Model Parameter Values

δf	Model Δcl max (αzl)	Model Δcl max (Δαzl)	Figure 131 no slats
0	0.00	0.00	
10	0.46	0.30	0.44
20	0.80	0.65	0.88
30			1.12
35	1.22	1.06	
40			1.24
45	1.52	1.37	

Figure 126 δf	Figure 126 αzl	Figure 126 Δ αzl	Figure 126 Δαzl δf	Figure 126 cl(α=0)
0	-2.0	0.0		0.18
10	-6.0	-4.0	-0.400	0.68
20	-10.5	-8.5	-0.425	1.22
35	-16.0	-14.0	-0.400	2.05
45	-20.0	-18.0	-0.400	2.49

δf	Figure 126 α max	Model α max	Figure 126 Δα max	Model Δα max	Figure 126 α range	Model α range	Figure 126 cl max	Model cl max (αzl)	Model cl max (dαzl)	Figure 126 clα (δf=0)	Model cl α (αzl)	Model cl α (Δαzl)
0	18.4	18.4	0.0	0.0	20.4	20.4	1.55	1.550	1.550	0.0760	0.0760	0.0760
10	13.6	14.8	-4.8	-3.6	19.6	20.8	1.80	2.006	1.854		0.0964	0.0891
20	12.0	12.8	-6.4	-5.6	22.5	23.3	2.39	2.348	2.196		0.1008	0.0943
35	10.0	10.8	-8.4	-7.6	26.0	26.8	2.81	2.766	2.614		0.1032	0.0975
45	9.6	9.2	-8.8	-9.2	29.6	29.2	2.98	3.070	2.918		0.1051	0.0999

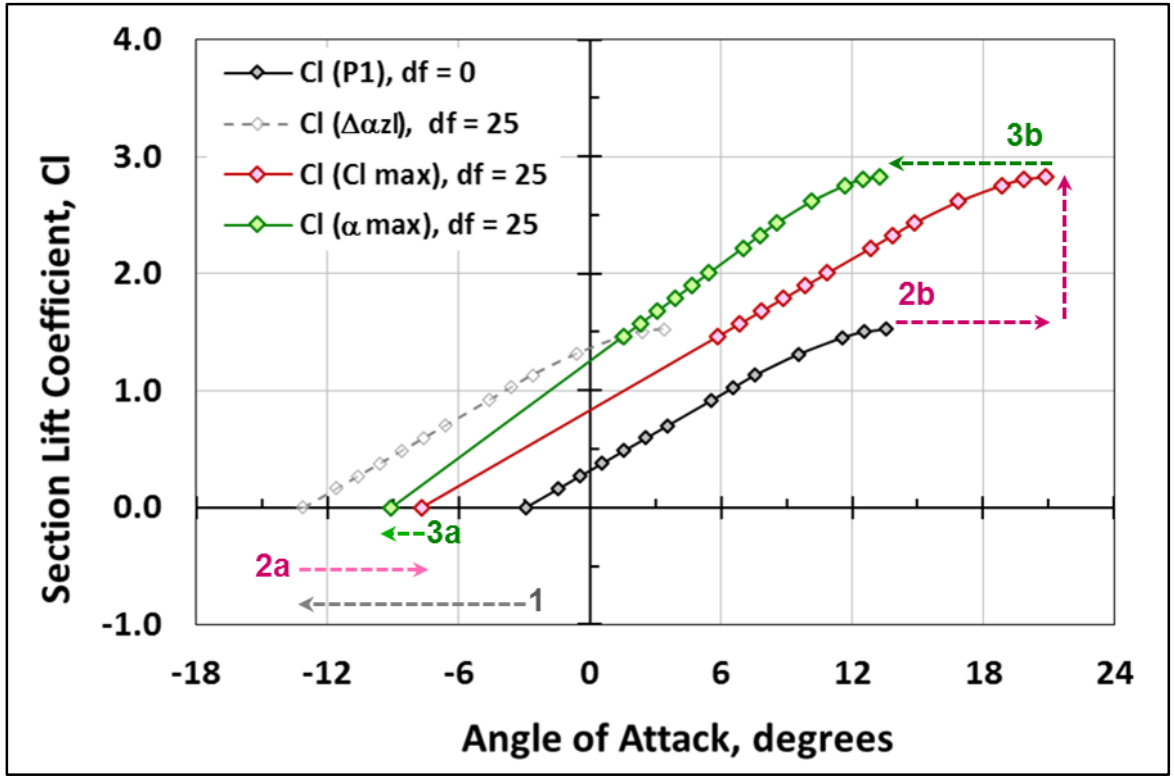


Figure 20. Airfoil aerodynamics modifications, maximum limits.

8.6 Generalized Validations: Wing Geometry, Aerodynamics, and Induced Drag

These validation tests were executed to assess the capability of MVL-15 to analyze 3d-wings of various aspect ratios, including sweep, dihedral, and taper. The geometry results for the tapered wing analyses are shown in Figure 21 through Figure 27. In addition, an elliptical planform was modeled and analyzed; however, the geometry output is not shown. The spanwise aerodynamics of the elliptical planform and tapered planforms are shown in Figure 28 and Figure 29, respectively. The spanwise aerodynamics were further analyzed to enable a comparison between the induced drag results for AR=10 wings with various taper ratios, and the theoretical elliptical induced drag value; the result is shown in Figure 30. Properly achieving this important comparison strongly validates the overall analysis capability of MVL-15.

Figure 31 highlights the effects of varying the wing tip convergence parameter for an AR=8, TR=.125 wing. It is evident from Figure 31 that this MVL-15 feature provides a well-behaved and realistic modification to the wing-tip lift (and has been shown to improve convergence significantly).

For all these validation cases, the nominal *p1* airfoil was used as the wing section. Examination of the results indicates that the fundamental results presented in Sections 8.2 and 8.3 have been extended to include modeling generalized wing planform geometry. At this point, the only remaining validation element is the analysis of two wings. Once complete, all validation cases can be combined for application to the aircraft configuration summary validation and analysis examples.

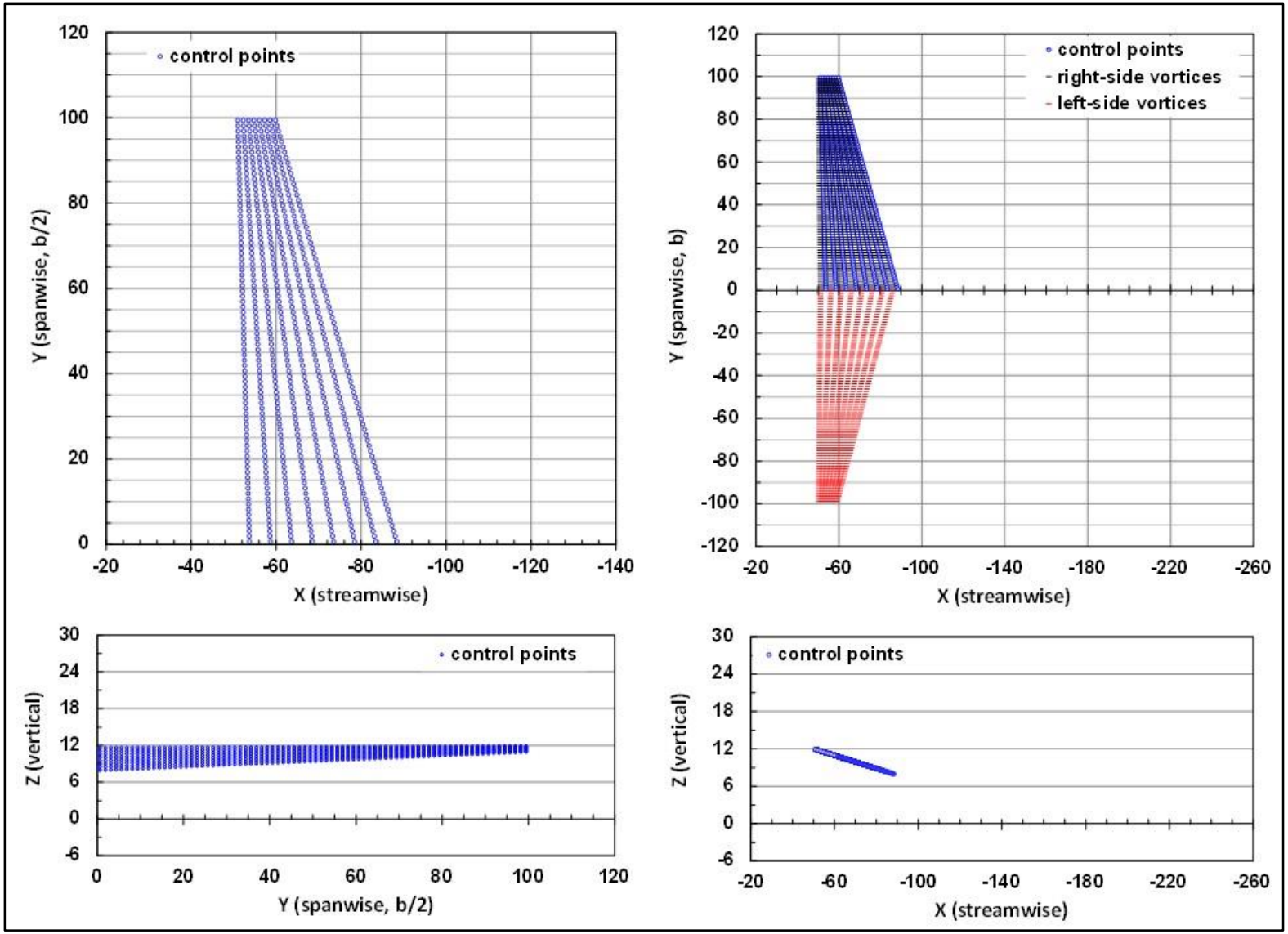


Figure 21. Two-panel wing: AR=8, TR=.25, dihedral=0.0/0.0 deg, sweep 0.0/0.0 deg.

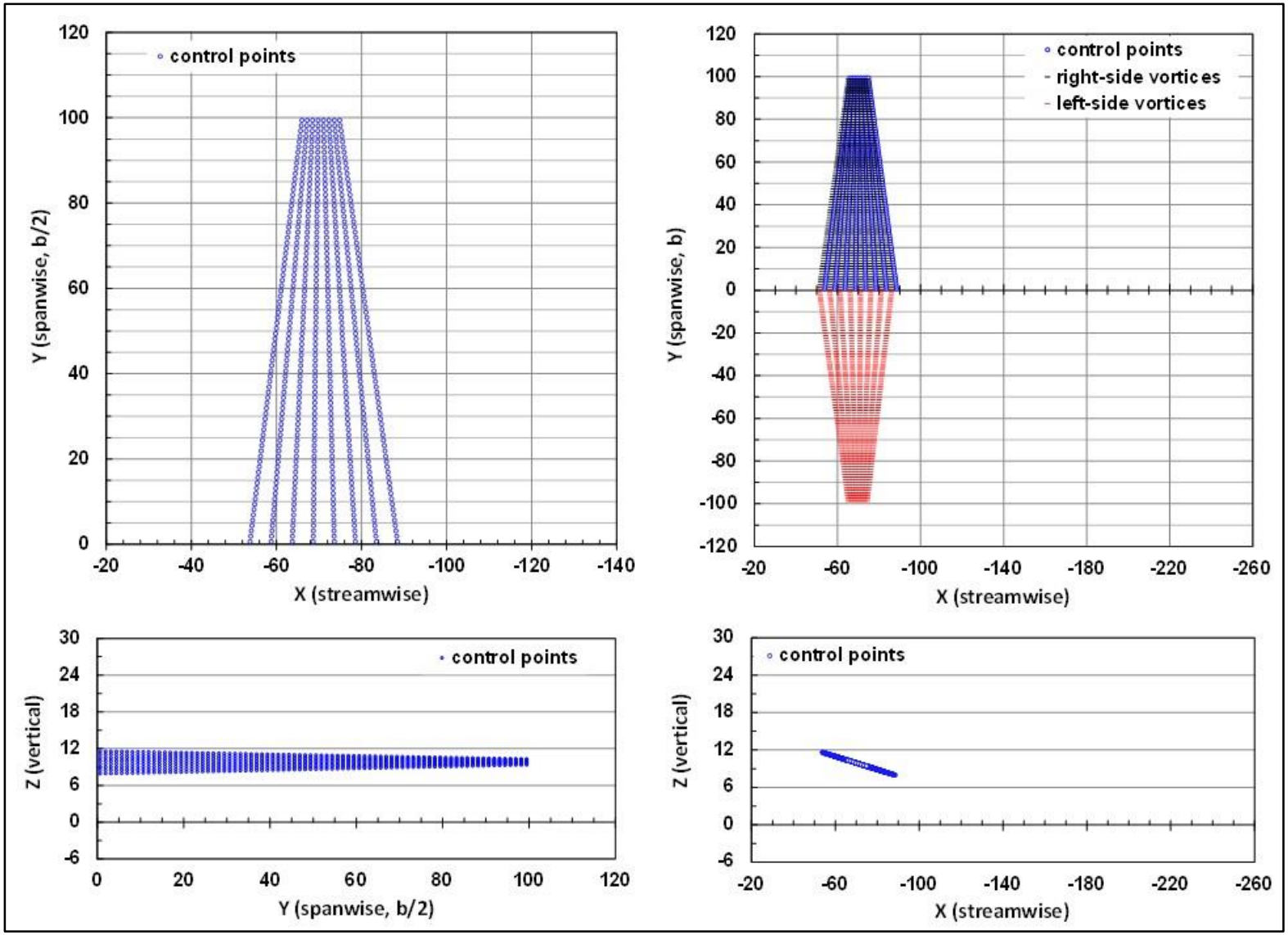


Figure 22. Two-panel wing: AR=8, TR=.25, dihedral=0.0/0.0 deg, sweep 8.6/8.6 deg.

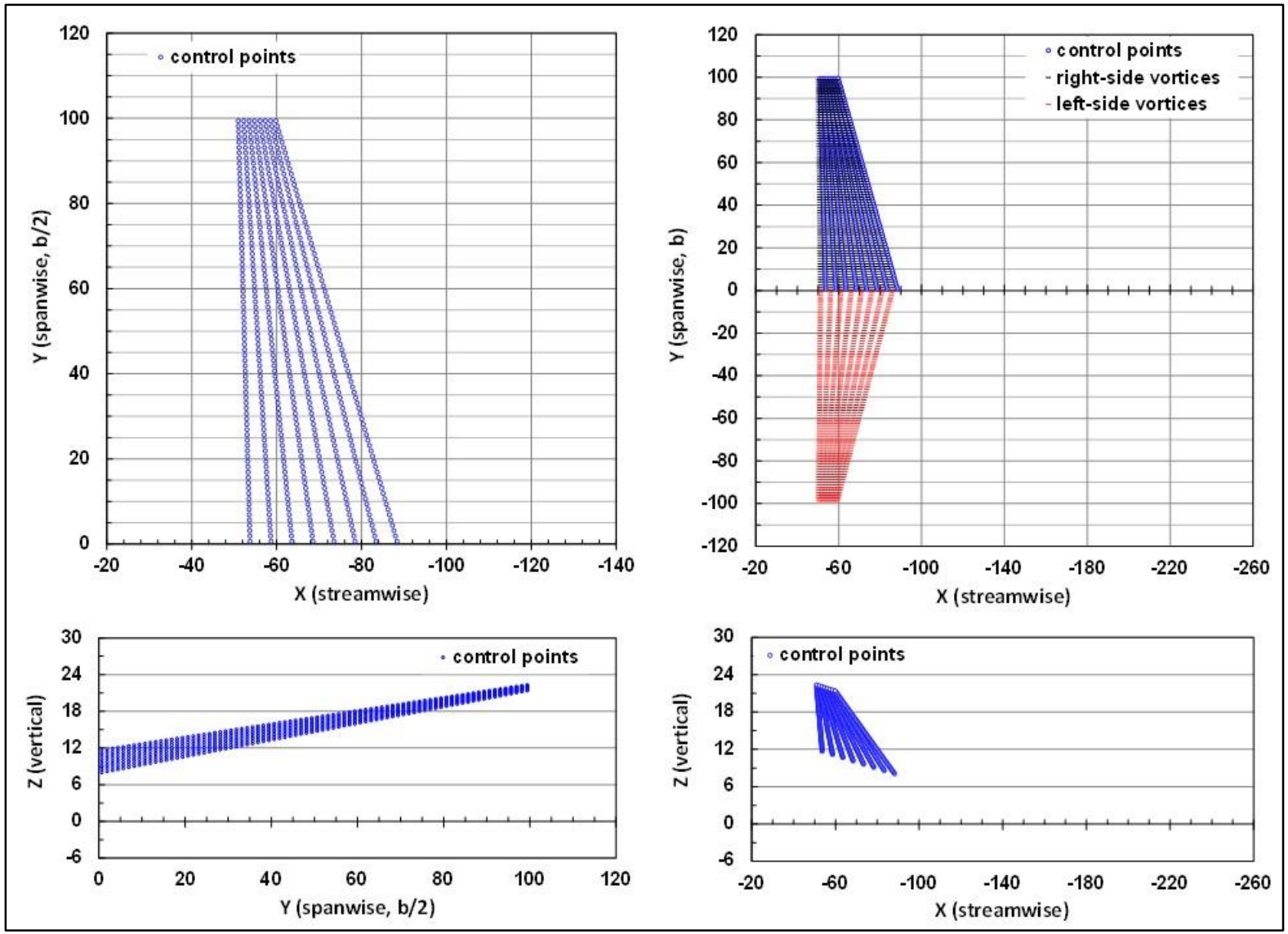


Figure 23. Two-panel wing: AR=8, TR=.25, dihedral=6.0/6.0 deg, sweep=0.0/0.0 deg.

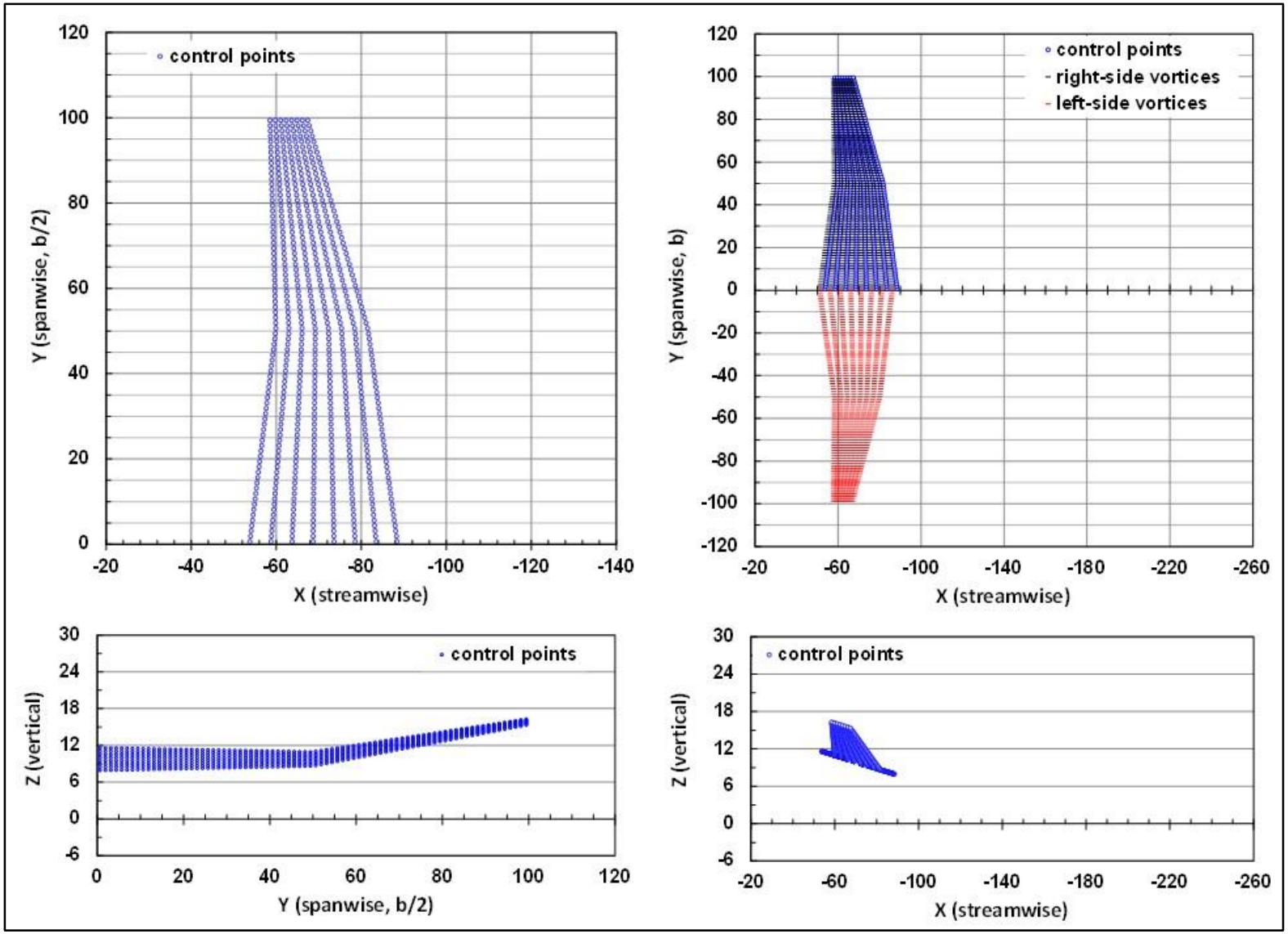


Figure 24. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep 8.6/0.0 deg.

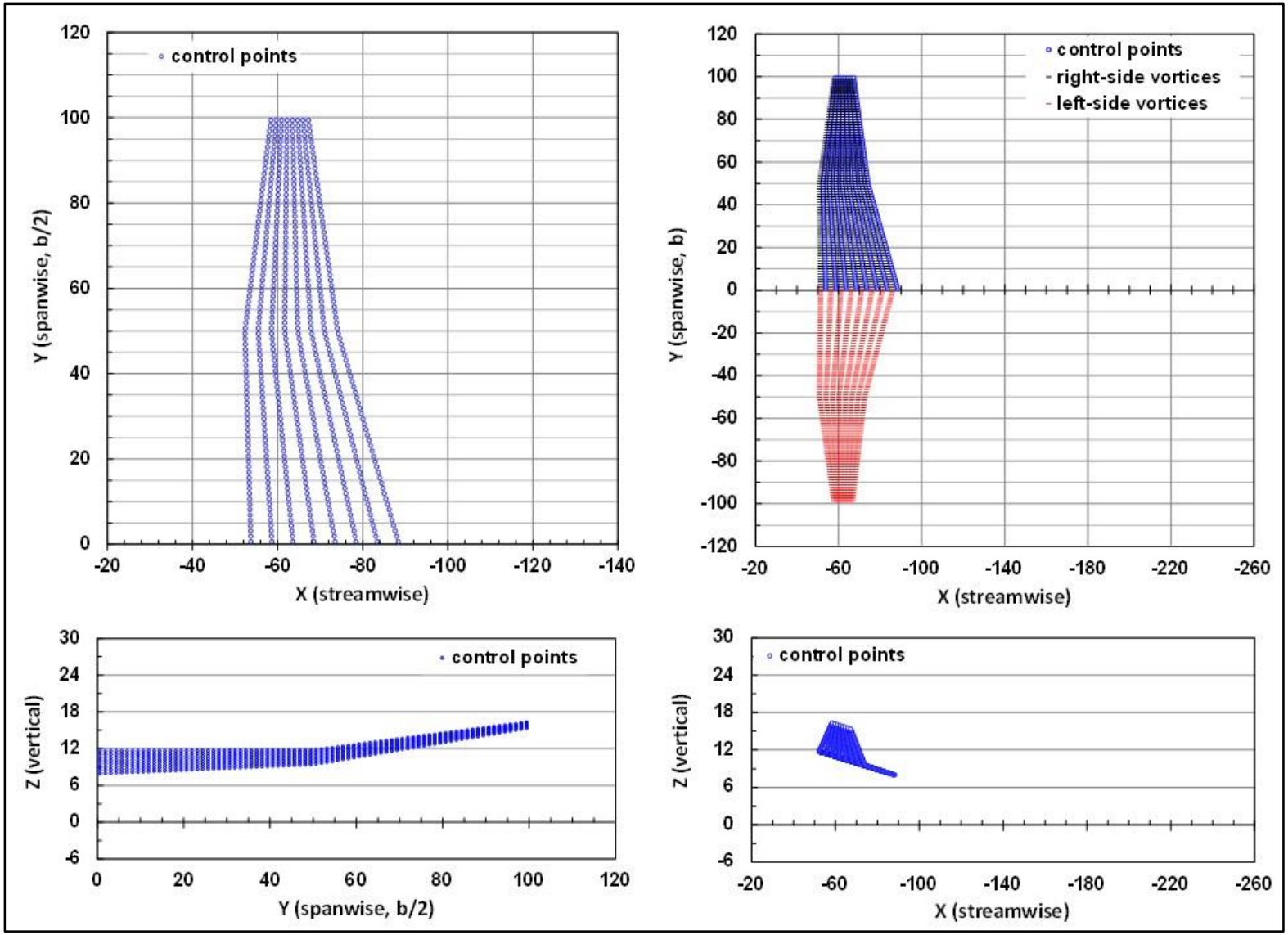


Figure 25. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep=0.0/8.6 deg.

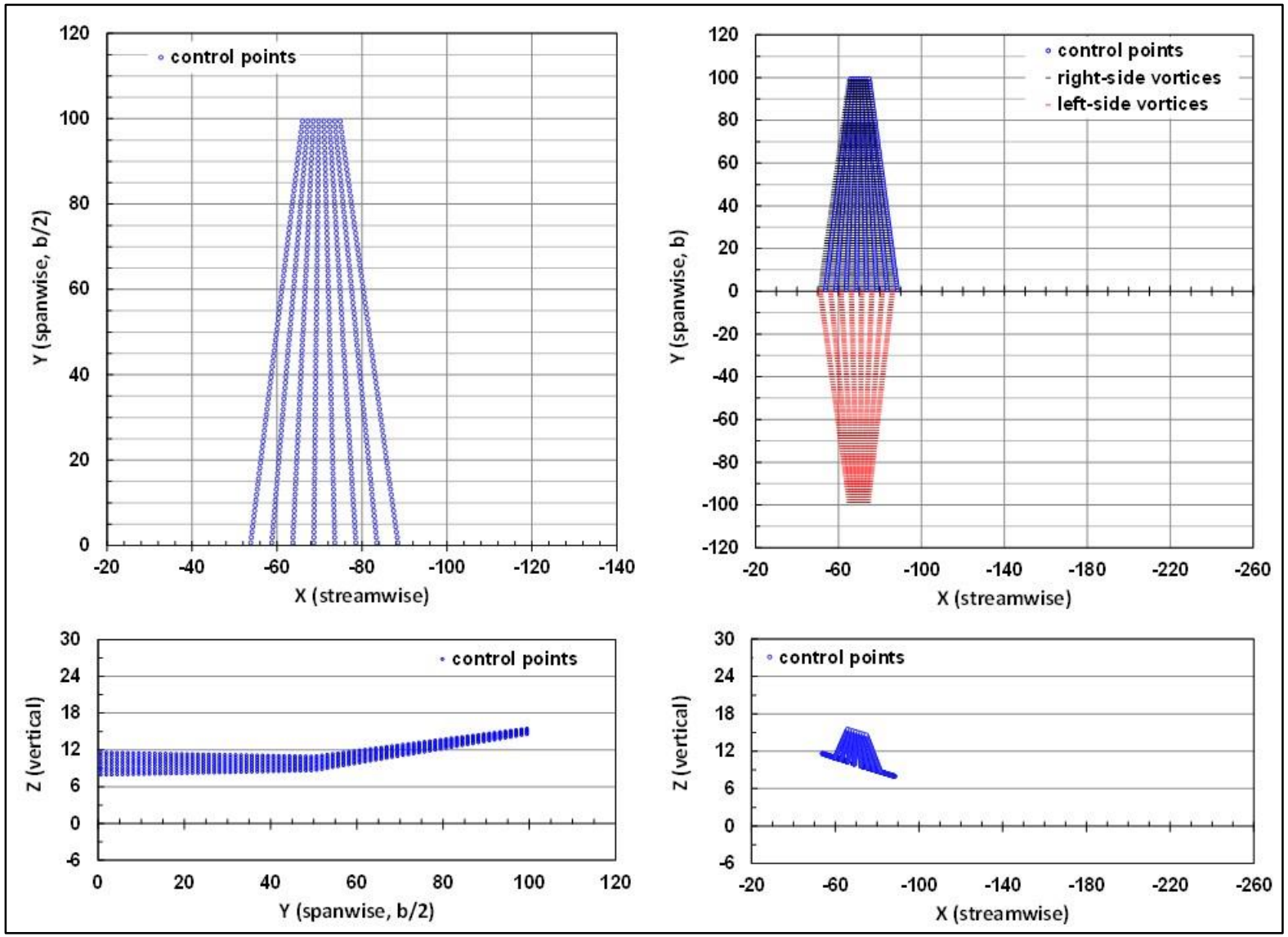


Figure 26. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep=8.6/8.6 deg.

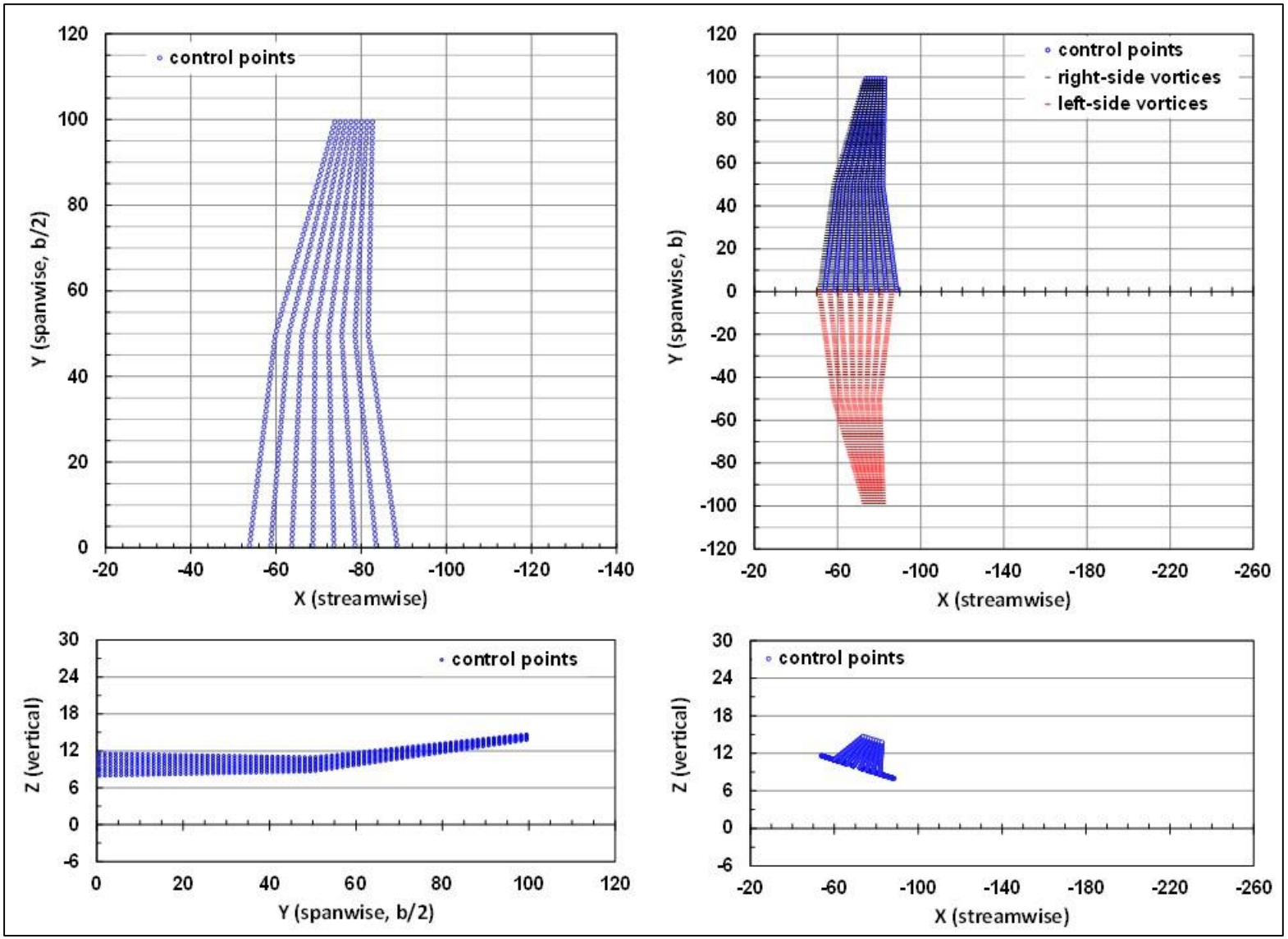


Figure 27. Two-panel wing: AR=8, TR=.25, dihedral=0.0/6.0 deg, sweep=8.6/17.2 deg.

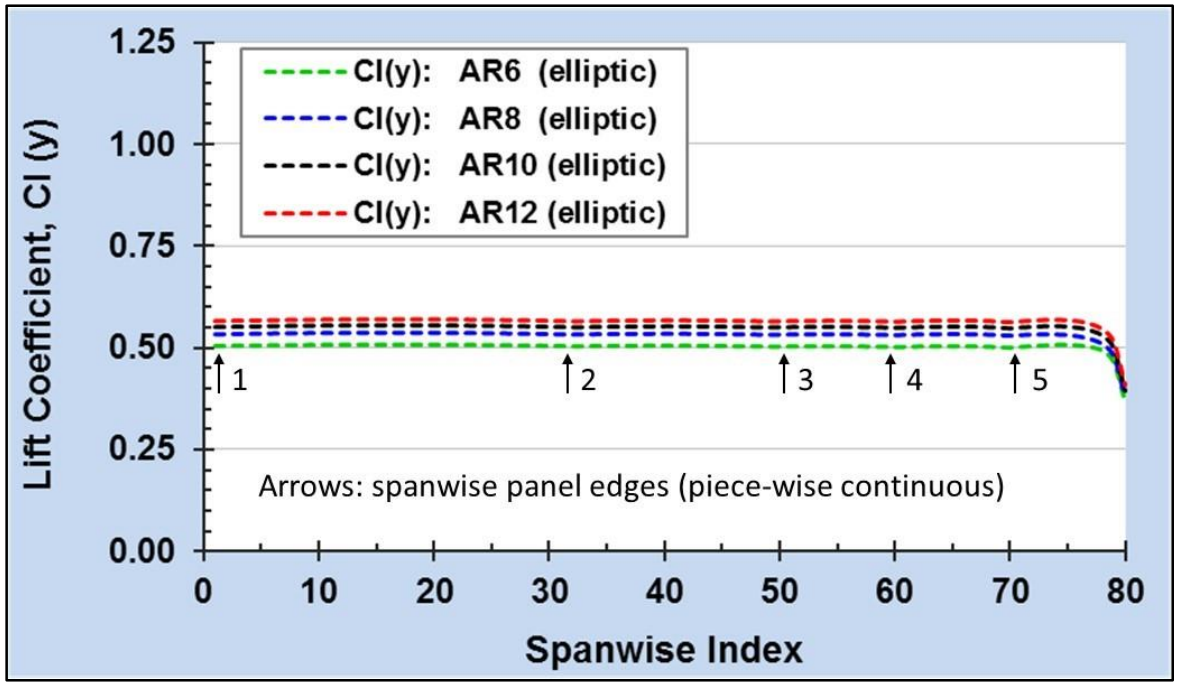


Figure 28. Elliptic wing spanwise lift, C_l (2y/b), as f (AR = 6, 8, 10, 12), ntip=0.

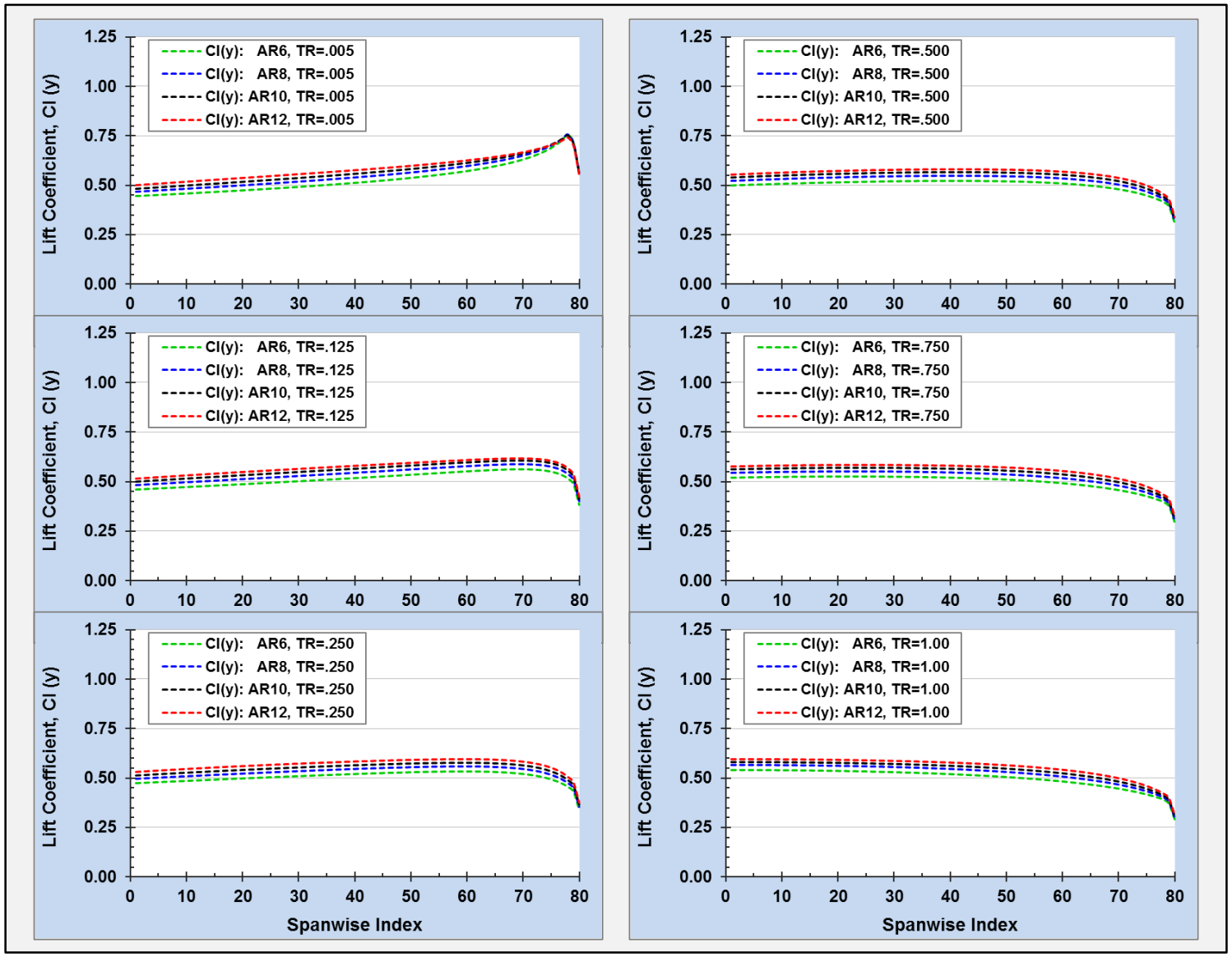
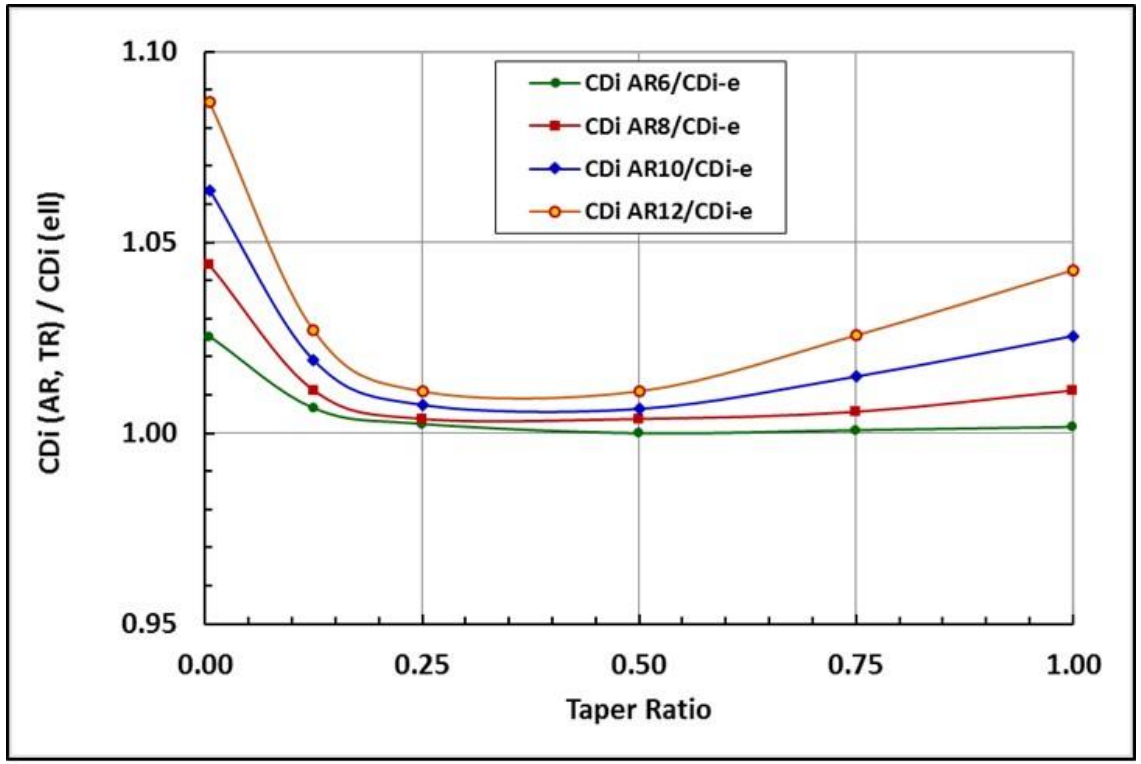


Figure 29. Spanwise lift, C_l (2y/b), as f (TR, AR = 6, 8, 10, 12), ntip=0.



MVL-15 CDi (AR, TR) / CDi (theory, elliptic) -- normalized by MVL-15 CDi elliptic wing

TR	CDi AR6/CDi-e	CDi AR8/CDi-e	CDi AR10/CDi-e	CDi AR12/CDi-e
0.005	1.0254	1.0440	1.0637	1.0867
0.125	1.0065	1.0112	1.0191	1.0269
0.250	1.0025	1.0037	1.0074	1.0110
0.500	1.0000	1.0037	1.0064	1.0110
0.750	1.0008	1.0056	1.0149	1.0256
1.000	1.0017	1.0112	1.0255	1.0427

Figure 30. C_{Di} comparisons as f (AR, TR).

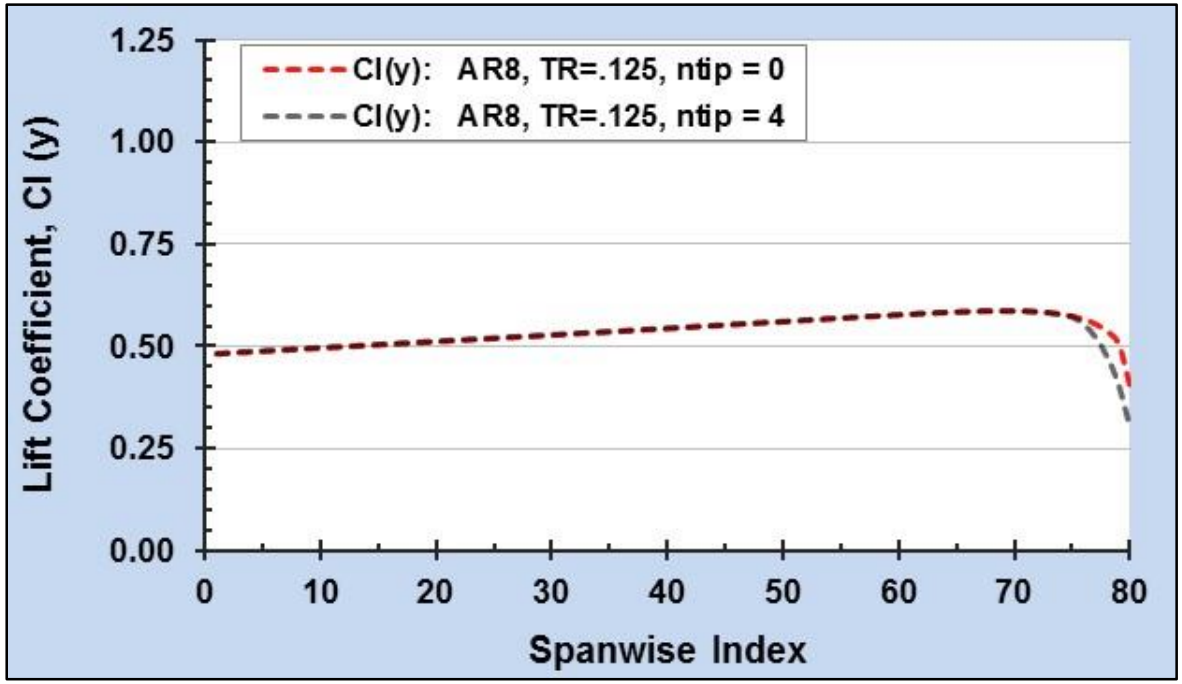


Figure 31. Spanwise lift, C_l (2y/b), TR=0.125, AR=8, tip comparison (ntip=0, ntip=4).

8.7 Aerodynamics Validation: Two Wings with Varying Relative Positions

The results of this section are similar to the results previously shown in Table 30 (Section 8.2) and Table 31 and Table 32 (Section 8.2). Table 36 summarizes the validation results of a 3d-analysis using *two* AR=1000 rectangular wings (c_o=1.0, b/2=500.0), modeled as a single spanwise panel per wing. For each case, the relative distance between the wing leading edges is highlighted by a red outline. Six validation cases were defined and grouped as three separate pairs. To test the results consistency within each pair, the odd-numbered cases were evaluated at α=0.0 degrees, and were associated with a 2d-section αzl=2.9232 degrees; the even-numbered cases were evaluated at α=2.9232 degrees, and were associated with a 2d-section αzl=0.0 degrees. All three pairs are shown to provide consistent results.

Figure 32 and Figure 33 depict the geometry and the spanwise lift distribution for these cases. Figure 33 indicates that the positioning of the wings leads to aerodynamic coupling in which the lift of the first wing increases and the lift of the trailing wing decreases. As the trailing wing separation distance increases, these effects decrease.

The magnitude and variation of this coupling was not decisively validated. Some uncertainty remains with the set up, analysis, and results interpretation of the limiting case when the leading edge of the second wing is positioned at the trailing edge of the first wing. As a result, further review of that limiting case might be a necessary consideration based on the future analysis needs. However, the effect is less evident as the separation increases, and other analyses not shown here indicate the coupling effect is reduced as the area of the second wing is reduced. Thus, the validation cases presented to this point indicate that MVL-15 is applicable to the analysis of an aircraft configuration. Section 8.8 will present the aircraft configuration validation and analysis examples.

Table 36. Aerodynamics of Two Wings: Varying the Relative LE Positions, α, and α*zl*

Case	Geometry 2d-name	Aero 2d-name	Section δsi	Section α-2d	Effective 2d α	OUTPUT > aero ref	S_wing	2d "AR"	2d αzl	CL Σ c Cl dy	CD-ind	Cdf-2d	CD-tot
2d-1	visc-f0	aero-0	0.0	0.0	0.0	**wing1**	1000.0	1000.0	0.0000	0.000	-	0.000	0.005
2d-2	visc-f29	aero-2923	2.9232	0.0	2.9232	**wing1**	1000.0	1000.0	2.9232	0.321	-	0.000	0.006
Case	**Geometry xLE/w-co-cf-cla**	**Aero 2d-name**	**Section 2d αzl**	**Wing α-3d**	**Effective 3d α**	**OUTPUT > aero ref**	**S_wing**	**Gm/Sk AR**	**α, deg**	**CL Σ c Cl dy**	**CD-ind**	**Cdf-2d**	**CD-tot**
1	20/1-1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	1000.0	350.2	0.0000	0.3502	-0.0017	0.0051	0.0068
	21/2-1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 2**	1000.0	177.3	0.0000	0.1773	0.0040	0.0055	0.0096
						S1 flap	1000.0	1000.0	0.0000	0.5275	0.0057	0.0106	0.0163
						S1 nofl	1000.0	1000.0	0.0000	0.5275	0.0057	0.0106	0.0163
						Sw aero	2000.0	500.0	0.0000	0.2637	0.0029	0.0053	0.0082
2	20/1-1-1-1	aero-0	0.0	2.9232	2.9232	**wing 1**	1000.0	350.1	2.9230	0.3501	-0.0017	0.0051	0.0068
	21/2-1-1-1	aero-0	0.0	2.9232	2.9232	**wing 2**	1000.0	177.5	2.9230	0.1775	0.0040	0.0055	0.0095
						S1 flap	1000.0	1000.0	2.9230	0.5276	0.0057	0.0106	0.0163
						S1 nofl	1000.0	1000.0	2.9230	0.5276	0.0057	0.0106	0.0163
						Sw aero	2000.0	500.0	2.9230	0.2638	0.0029	0.0053	0.0081
3	20/1-1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	1000.0	357.8	0.0000	0.3578	-0.0022	0.0051	0.0072
	23/2-1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 2**	1000.0	259.2	0.0000	0.2592	0.0025	0.0053	0.0078
						S1 flap	1000.0	1000.0	0.0000	0.6169	0.0047	0.0103	0.0150
						S1 nofl	1000.0	1000.0	0.0000	0.6169	0.0047	0.0103	0.0150
						Sw aero	2000.0	500.0	0.0000	0.3085	0.0023	0.0052	0.0075
4	20/1-1-1-1	aero-0	0.0	2.9232	2.9232	**wing 1**	1000.0	357.1	2.9230	0.3571	-0.0021	0.0051	0.0072
	23/2-1-1-1	aero-0	0.0	2.9232	2.9232	**wing 2**	1000.0	259.2	2.9230	0.2592	0.0025	0.0052	0.0077
						S1 flap	1000.0	1000.0	2.9230	0.6163	0.0046	0.0103	0.0149
						S1 nofl	1000.0	1000.0	2.9230	0.6163	0.0046	0.0103	0.0149
						Sw aero	2000.0	500.0	2.9230	0.3082	0.0023	0.0051	0.0075
5	20/1-1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 1**	1000.0	344.6	0.0000	0.3446	-0.0014	0.0051	0.0064
	25/2-1-1-1	aero-29	-2.9232	0.0	2.9232	**wing 2**	1000.0	282.8	0.0000	0.2828	0.0017	0.0052	0.0069
						S1 flap	1000.0	1000.0	0.0000	0.6274	0.0030	0.0103	0.0133
						S1 nofl	1000.0	1000.0	0.0000	0.6274	0.0030	0.0103	0.0133
						Sw aero	2000.0	500.0	0.0000	0.3137	0.0015	0.0051	0.0067
6	20/1-1-1-1	aero-0	0.0	2.9232	2.9232	**wing 1**	1000.0	344.0	2.9230	0.3440	-0.0013	0.0051	0.0064
	25/2-1-1-1	aero-0	0.0	2.9232	2.9232	**wing 2**	1000.0	282.6	2.9230	0.2826	0.0017	0.0052	0.0068
						S1 flap	1000.0	1000.0	2.9230	0.6266	0.0030	0.0102	0.0132
						S1 nofl	1000.0	1000.0	2.9230	0.6266	0.0030	0.0102	0.0132
						Sw aero	2000.0	500.0	2.9230	0.3133	0.0015	0.0051	0.0066

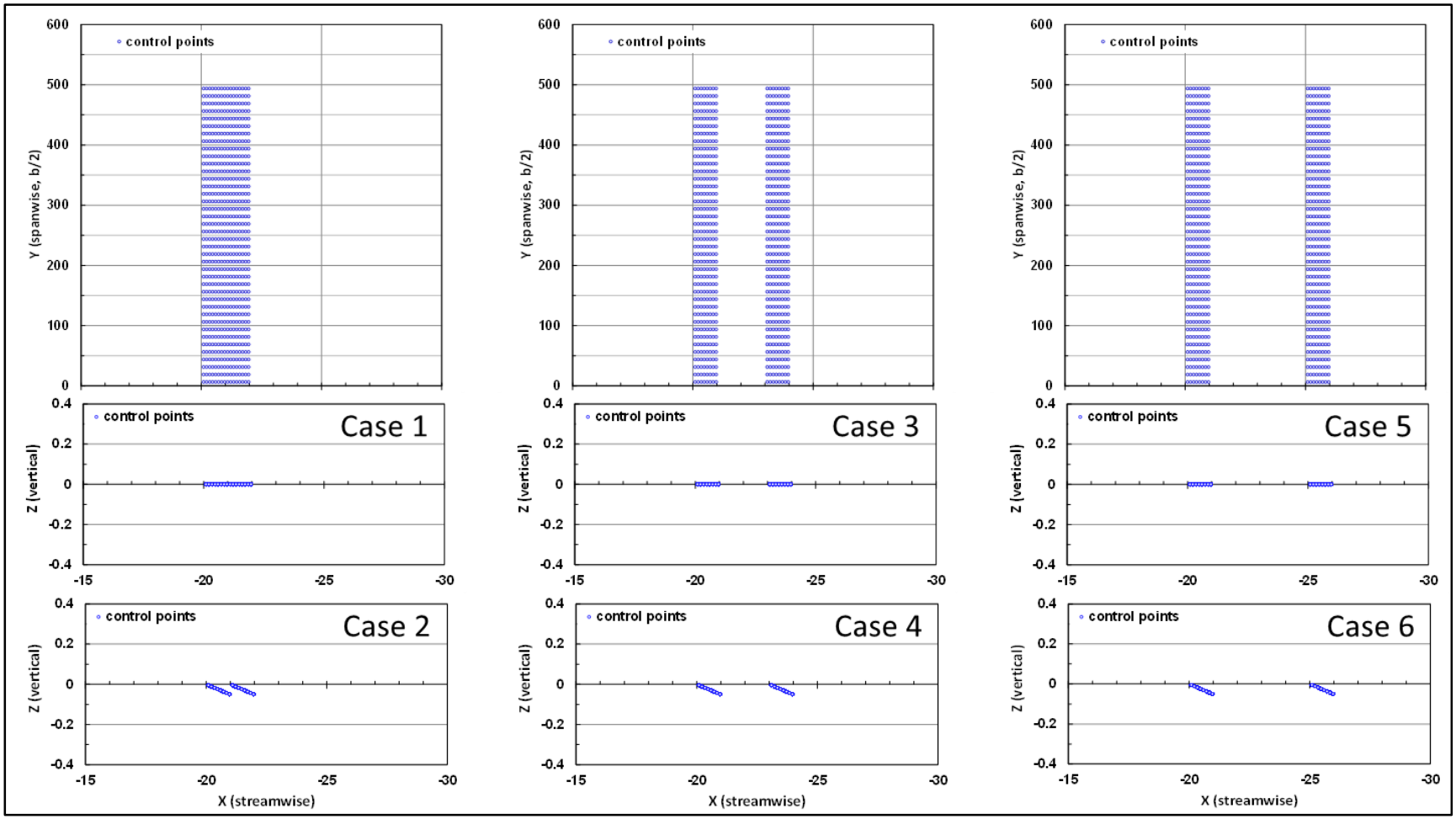


Figure 32. Figure to illustrate the geometry listed in Table 36.

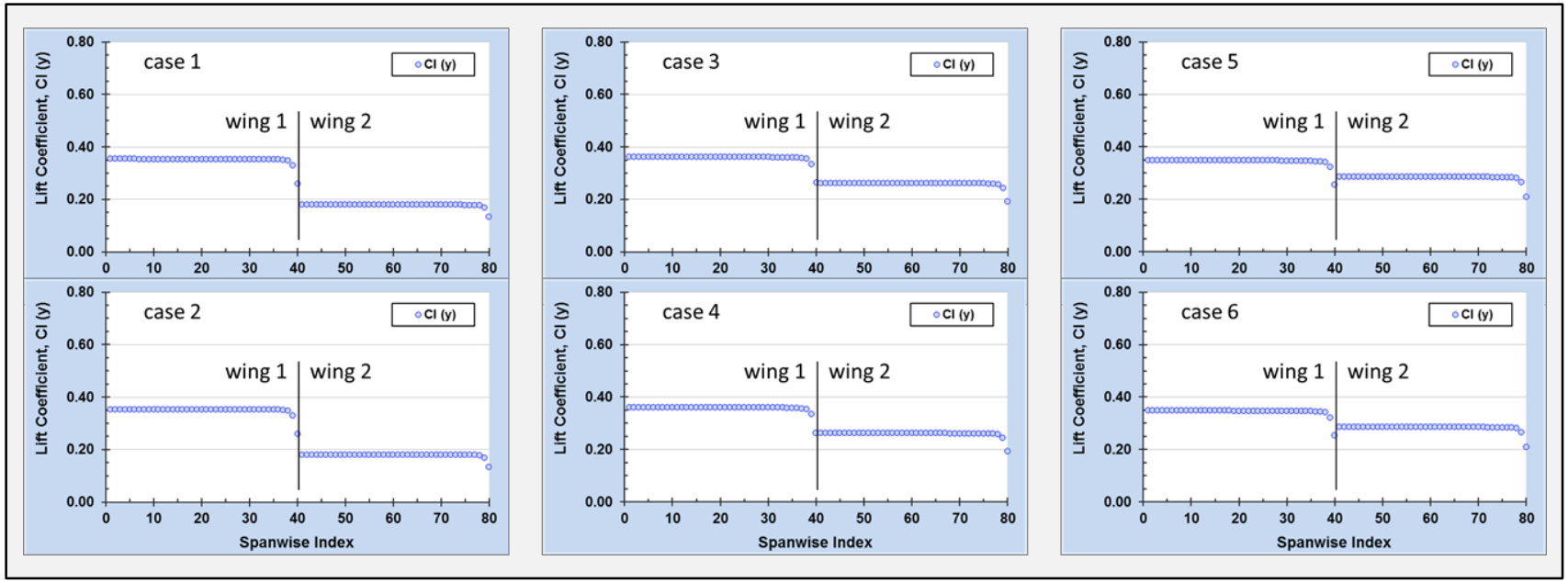


Figure 33. Spanwise lift for the validation cases listed in Table 36.

8.8 Analysis Procedure: Airplane Takeoff and Approach Example

The final set of validation cases were based on the analysis of an aircraft configuration representative of the aircraft analyzed during the ERA project. The charts shown in these figures were generated using the *3d-Results Presentation Utility*. Figure 34 through Figure 38 illustrate results from the analyses of an aircraft configured for takeoff and approach. Comparisons are made with proprietary data for a similar aircraft. These validation results indicate that the MVL-15 analysis tool is suitable for use analyzing the aerodynamics of an airplane configured for takeoff and approach.

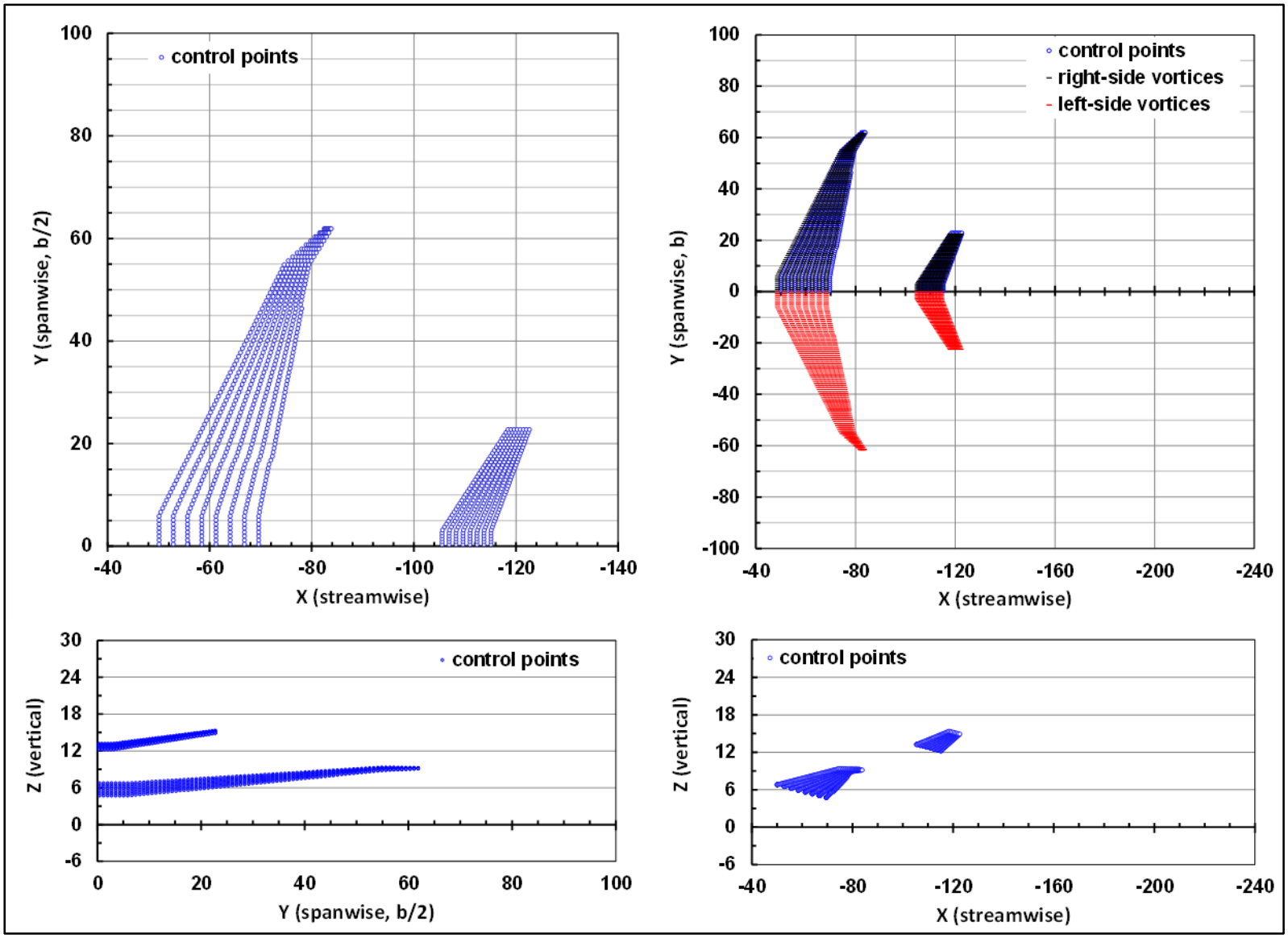


Figure 34. Airplane takeoff geometry.

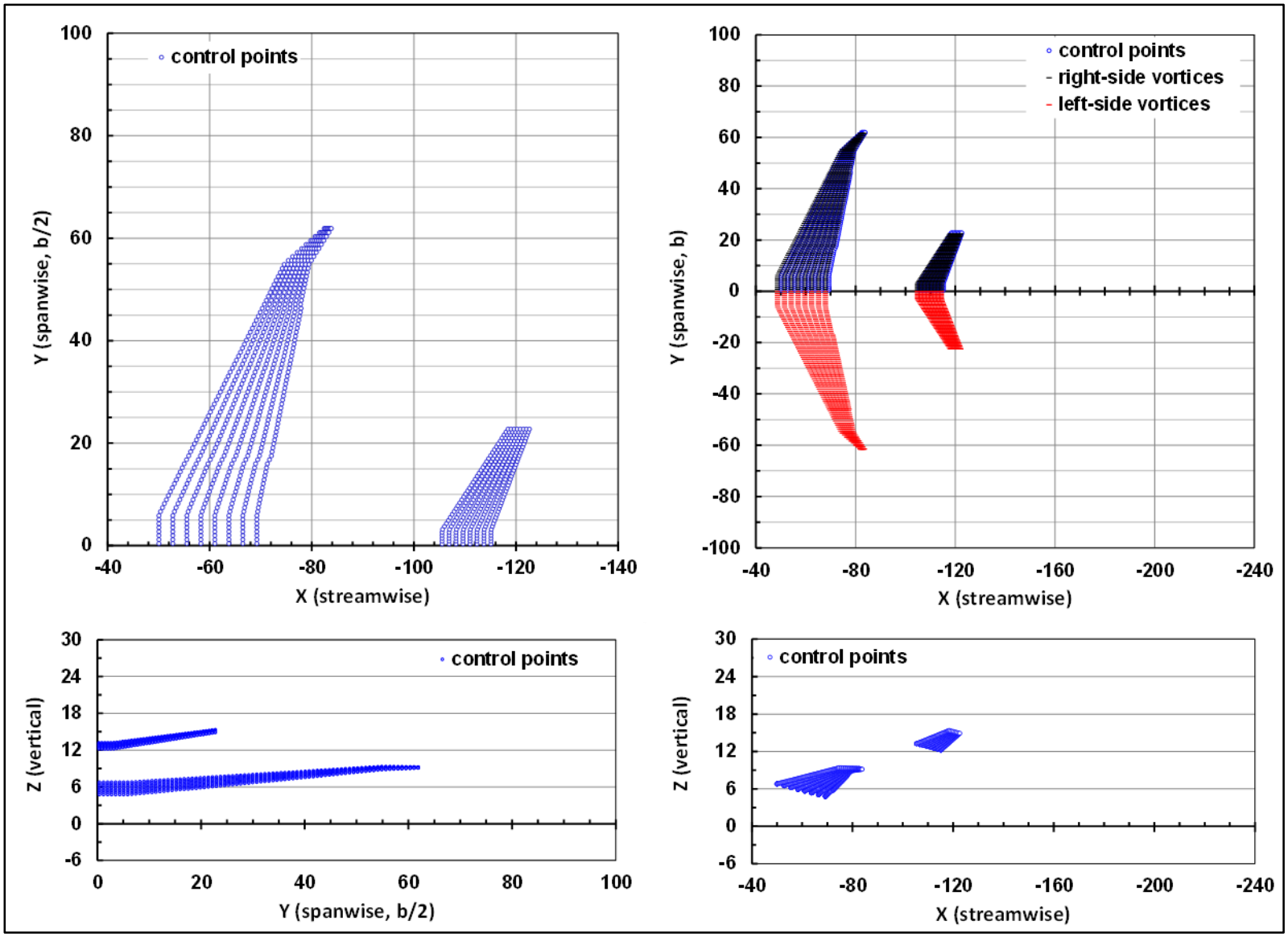


Figure 35. Airplane approach geometry.

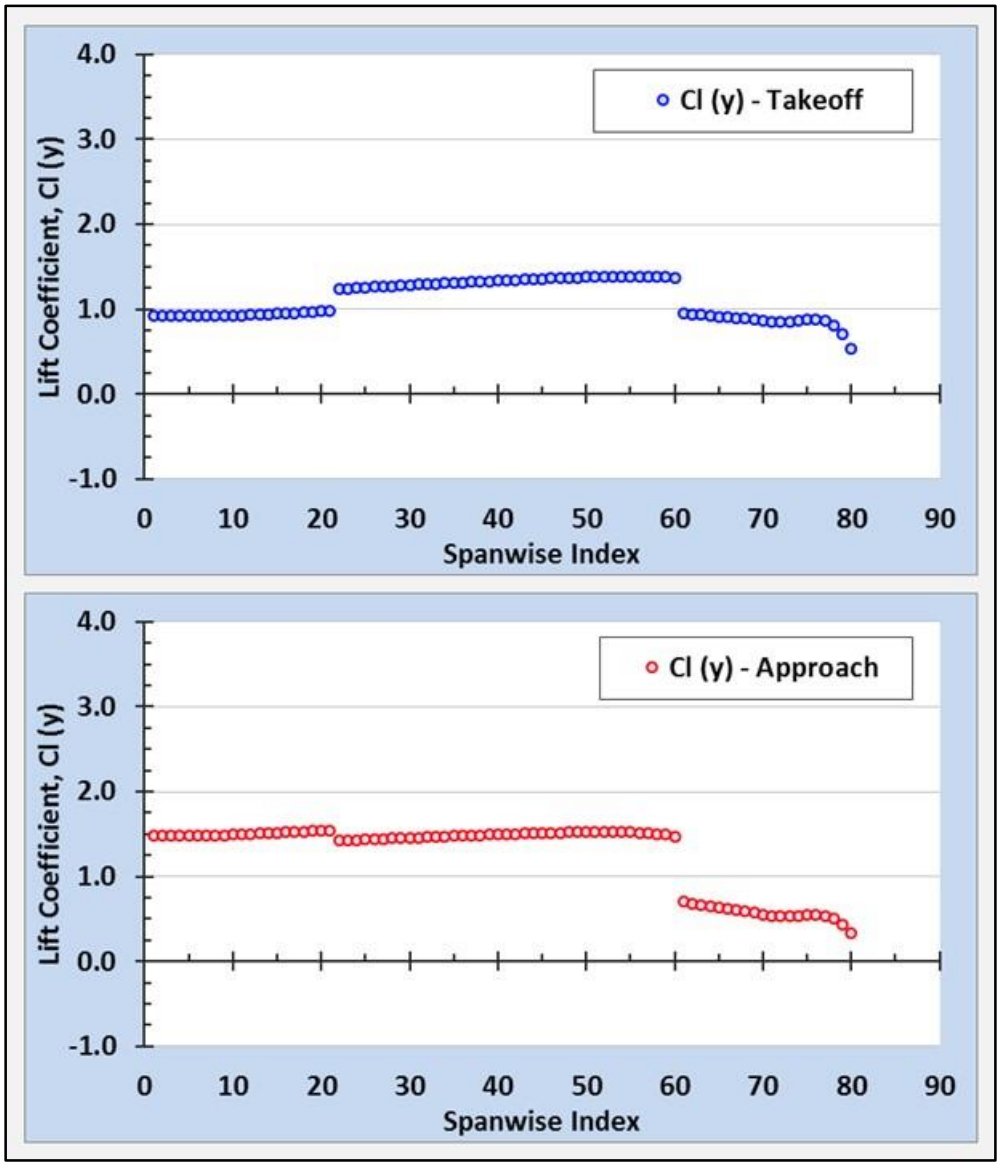


Figure 36. Airplane takeoff and approach spanwise lift, C_l (2y/b).

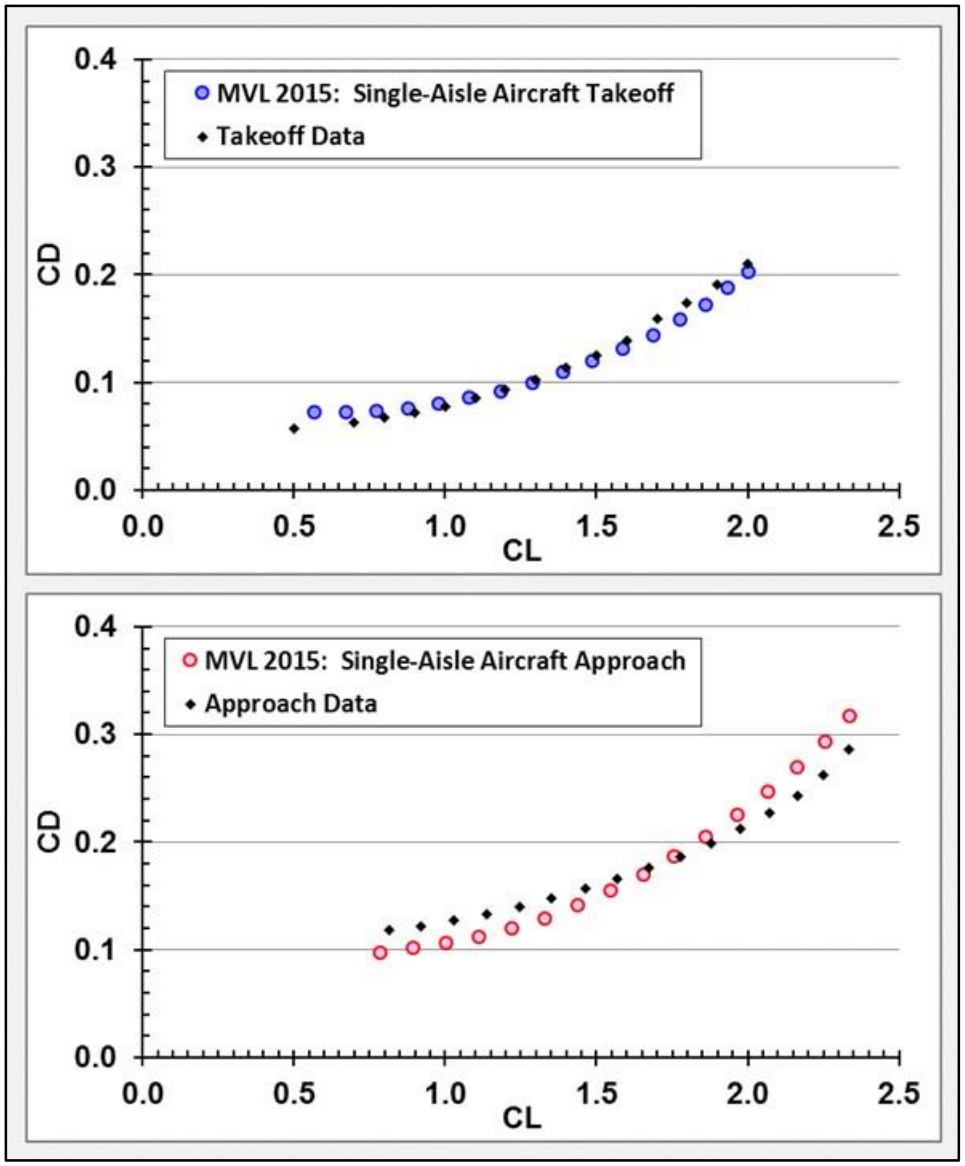


Figure 37. Airplane takeoff and approach drag polars, C_D vs. C_L.

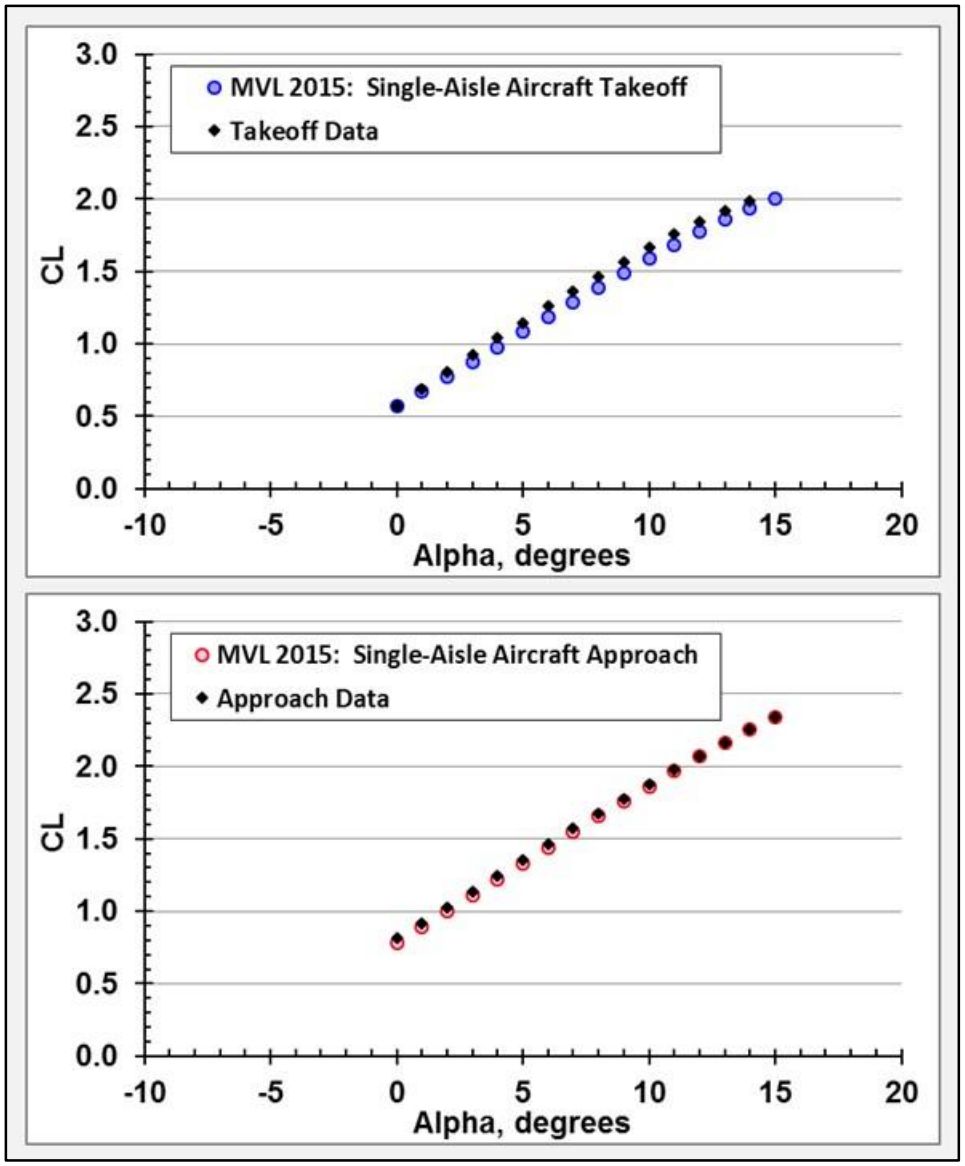


Figure 38. Airplane takeoff and approach lift curves, $C_{L\alpha}$.

References

1. McCormick, B.W.: *Aerodynamics, Aeronautics, and Flight Mechanics*. J. Wiley and Sons, Inc., 1979.

2. Karamcheti, K.: *Principles of Ideal Fluid Aerodynamics*. J. Wiley and Sons, Inc., Reprinted, 1980.

3. Bertin, J. J. and Smith, M. L.: *Aerodynamics for Engineers*. Prentice-Hall, Inc., 2nd Edition, 1989.

4. Abbott, I. H. and von Doenhoff, A.E.: *Theory of Wing Sections-Including a Summary of Airfoil Data*. Dover Publications, Inc., 1959.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01- 11 - 2015	Contractor Report	

4. TITLE AND SUBTITLE

Description, Usage, and Validation of the MVL-15 Modified Vortex Lattice Analysis Capability

5a. CONTRACT NUMBER

NNL12AA09C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Ozoroski, Thomas A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

338881.02.07.07.08

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NASA Langley Research Center
Hampton, Virginia 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)

NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

NASA/CR-2015-218969

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified
Subject Category 01
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

Langley Technical Monitor: Craig L. Nickol

14. ABSTRACT

A Modified Vortex Lattice method (MVL-15) has been developed which includes a method to link the inviscid analytic results at spanwise wing locations to empirically-derived viscous aerodynamic data. Normally outside the scope of vortex-lattice codes, the viscous modifications extend the analysis application to include non-linear effects occurring at high lift conditions. The code accepts parameterized airfoil and wing geometry inputs, including camber, twist, angle of attack, dihedral, sweep, and taper. A total of five wings, each with five different section properties can be modeled.

15. SUBJECT TERMS

Aerodynamics; Low speed; Vortex lattice; Wing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	116	(757) 864-9658